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Final Report

SOURCES, MEASUREMENT, AND EFFECTS OF SEGREGATED HOT MIX ASPHALT PAVEMENT

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HPR-2066

by

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16. Abstract

There are several factors that lead to segregation. Segregation can occur during stockpiling and handling of aggregate and during mixing, storage, transport, and laydown of the asphalt mixture. Sometimes segregation may result from a single source or from a combination of sources.

Nondestructive test methods have been examined to determine their effectiveness in detecting segregation. These methods include thermal imaging, air permeability, nuclear moisture (asphalt) and density, and permitivity. Based on the effectiveness of these technologies in a laboratory environment, the standard moisture/density nuclear gauge technology was field tested with a high degree of success. Use of four minute gauge readings is recommended.

Field testing with the nuclear moisture/density gauge was conducted on four projects. Random locations and areas visually identified as segregated were tested with a nuclear moisture/density gauge. Subsequently, cores from the same locations where the nuclear gauge moisture (asphalt) content and density readings were taken for laboratory evaluation. A draft specification for detecting segregation is recommended using a nuclear moisture/density gauge.

Asphalt mixture segregation results in distresses such as raveling, stripping, rutting, and cracking developing prematurely. Relative performance of mixtures with varying levels of segregation were determined through repeated flexural fatigue and accelerated wheel track testing. The most significant reduction in pavement performance through flexural fatigue and accelerated wheel track testing comes from coarse segregation.

A training video was prepared for the Indiana Department of Transportation as one of the research tasks. A copy of this video, "Hot Mix Asphalt Segregation," can be obtained by calling the Joint Highway Research Project at 317/494-9310. Recommendations for future research from this study are also outlined.

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IMPLEMENTATION REPORT

This research project has demonstrated that nuclear gauge testing of visually identified segregated areas is very effective in quantifying segregation and should be implemented. Based upon field testing with four minute nuclear gauge readings of density and moisture (asphalt) content, coarse segregation was identified with perfect accuracy. The following implementation of nuclear gauge testing to confirm visual identified segregation is recommended.

1. A standard background count is taken before use on a daily basis to check gauge operation and allow for source decay. The new count will pass if plus or minus two percent of the moisture average and/or plus or minus one percent of the density average. The operating manual should be consulted to ensure safe operating procedures.
2. The gauge is operated in backscatter mode. Further, the gauge is operated in the soil mode allowing for both density and moisture (asphalt) content measurements.
3. Analysis of coarse segregation is visually identified by an inspector. This area of coarse segregation is defined as an area having considerably more coarse aggregate than the surrounding acceptable mat and contains little or no mastic. Figure I.1 identifies such an area.

4. A nuclear gauge is placed on the subject location and concurrent four minute readings of density and moisture (asphalt) content are recorded.
5. The density reading is subtracted from the job mix formula target density. This value is referred to as the "Difference in density from the JMF."
6. The moisture (asphalt) content reading is subtracted from the job mix formula target asphalt content. This value is referred to as the "Difference in asphalt content from the JMF."
7. The values obtained in steps 5 and 6 are plotted on Figure I.2 titled "Visual Coarse Segregation Classification Based on 4 Minute Nuclear Gauge Readings."
8. If the plotted point falls below the 90 percent posterior probability line (90 PP), the location is identified as being coarsely segregated.

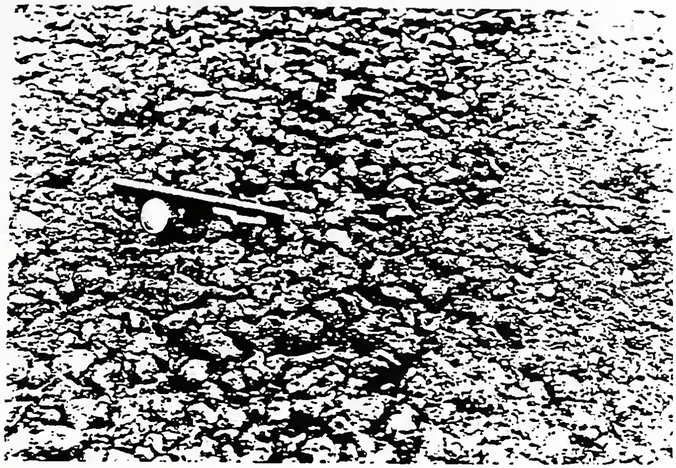

Figure I.1 Visual Coarse Segregation

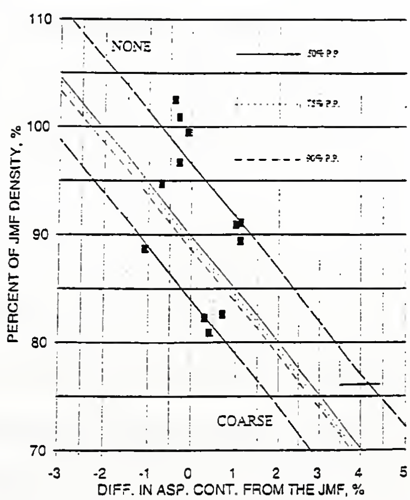

Figure I.2 Visual Coarse Segregation Classification Based on 4 Minute Nuclear Gauge Readings

CHAPTER 1. INTRODUCTION

1.1 Background

Early distress of asphalt surfaces has been associated with asphalt mixture segregation. Asphalt mixture segregation is the nonuniform distribution of coarse and fine aggregate components. Because of the nonuniform distribution, distresses such as raveling, stripping, rutting and cracking can develop prematurely. There are several sources that can lead to segregation. Segregation can occur during stockpiling and handling of aggregate, in the mixture during asphalt plant processing, storage, transport, and laydown. Segregation can result from a single source or a combination of sources. This segregation leads to distress, loss of serviceability or loss of structural capacity.

1.2 Scope

A test that identifies asphalt mixture segregation would be a significant contribution to asphalt technology. Non-destructive test methods were examined under laboratory conditions to determine their effectiveness in detecting segregation and their sensitivity in the measurement. These methods will include thermal imaging, air permeability, nuclear moisture(asphalt) and density, and permittivity. Based upon their effectiveness in a laboratory environment, preliminary field testing will be conducted to

evaluate their sensitivity under field conditions.

Equally important to detecting segregation is the impact of segregation on pavement performance. The performance of mixtures with varying levels of segregation were determined through repeated flexural and accelerated wheel track testing.

1.3 Objective

Objectives of this study include: 1. characterization of segregated mixtures, 2. identification of a technology or combination of technologies that detects segregation, 3. implementation of this technology, and 4. establishment of the relative reduction in pavement performance due to segregation. This study will involve both laboratory and field investigations. The following tests and evaluations are planned on laboratory prepared specimens:

- i.) Gradation analyses.
- ii.) Density and asphalt content determination.
- iii.) Air voids analyses.
- iv.) Nuclear moisture (asphalt) content and density measurements.
- v.) Repeated flexural testing.
- vi.) Accelerated wheel track testing.

The following tests will be performed on field specimens:

- i.) Nuclear moisture (asphalt) content and density measurements.
- ii.) Density and asphalt content determination.

iii.) Gradation analyses.

1.4 Report Organization

Chapter two discusses the literature review on segregation, its measurement and effect. Chapter three provides a summary of the state of practice survey results and the development of the training video. Chapter four evaluates potential technologies and their effectiveness to detect segregation. Chapter five describes the technologies studied in a laboratory environment to detect segregation. Chapter six explains the field data collection and describes laboratory tests on field cores. Fatigue testing of segregated mixtures is discussed in Chapter seven. Chapter eight covers the accelerated wheel track testing of segregated mixtures. The conclusions of the study with recommendations for future research are outlined in Chapter nine.

1.5 Implementation

Implementation of the results and recommendations in this study is expected to assist INDOT in detecting segregated mixtures. Further, reduction in pavement performance based upon degree of segregation will be established for some mixtures. This will assist INDOT in implementing a more effective quality control/quality assurance program. Overall this will result in tax dollar savings.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

Segregation is a significant asphalt pavement deficiency that can cause poor performance (Roberts et al., 1991). Segregation can occur from a number of different steps in the hot mix asphalt (HMA) production and placement process. These steps include the mixture design, aggregate stockpiling, plant production, HMA storage, truck loading, transport, and laydown (Brock, 1986).

2.2 Segregation Studies

Historically, segregation is a relatively new research topic in hot mix asphalt (HMA) pavement. Segregation was addressed by Bryant (1967). Bryant concluded that HMA segregation is a major contributing factor to variation in extracted asphalt percentages. This is a result of the great difference in surface area of the coarse and fine fractions of the mixture along with the propensity of the fine fraction to form a mastic which holds more asphalt.

It was not until Brock (1986) summarized that segregation is a common and consistent problem that the topic begin receiving significant attention. Texas and

Georgia studied segregation in the late 1980's (Kennedy et al., 1986 and Brown et al., 1988).

The Texas study focused on identifying sources of segregation, why it occurred in particular production steps, and corrective measures to reduce segregation once identified visually. The study summarized that equipment and techniques developed to help eliminate segregation will only work if mixing plants and equipment are operated properly and are adjusted for the particular plant production needs. It was also stated that elimination of segregation due to one cause may expose another problem. Paving operations were also examined. The point was made that maintaining uniform laydown machine operation with a constant level of material above the auger is important in reducing segregation.

In a study of Georgia mixtures (Brown et al., 1988) mixes were tested in the laboratory to characterize their physical properties. Among the relationships that were found was that as a mixture becomes more coarsely segregated, voids in the total mix increased. Secondly, the index of retained stability from an immersion compression test decreased with an increase in coarse segregation. The index of retained stability for a specified level of segregation was based on two sets of compacted Marshall specimens, a conditioned set and an unconditioned set. The conditioned set was soaked for 24 hours in a water bath at 140°F. The unconditioned set were soaked for 30 minutes in a 140°F water bath for 30 minutes before being testing in the Marshall apparatus. The index of retained stability is the stability of the conditioned set divided by the stability of the unconditioned set. Brown also examined the effect of segregation on the stability of the

unconditioned set. Initially, stability increased with coarse segregation, then decreased significantly. This same trend was true when the indirect tensile strength of the same mixes were examined. They concluded that the decrease in stability associated with coarser levels of segregation indicates potentially more rutting and/or raveling of the pavement because of deviations in the amount of material passing the No. 200 sieve.

In analysis of coarsely segregated mixtures in the field, Brown (Brown et al., 1988) examined the percent passing the #8 sieve to classify segregation. Samples from in-place HMA were compared to plant samples. Plant samples from a number of different projects showed a range in percent passing the #8 sieve from 33 to 48 percent.

Cross and Brown (1993) studied the effect of segregation on the amount of raveling. They concluded that a variation in the percent passing the #4 sieve greater than 8 to 10 percent can lead to raveling. They correlated visual observations of segregation with pavement surface macro-texture. In the correlation, the total traffic as measured by the adjusted average daily traffic had an effect on macro texture. A raveled depth of 0.50 mm or greater was measured. Thus, traffic on segregated areas influenced raveling. The data was obtained from projects known to have segregation problems. The final point that Cross and Brown conclude is that visual means can identify the lateral extent of segregation with respect to material passing the No. 4 sieve. Their visually identified segregated samples had a lower percent passing the No. 4 sieve than random samples.

2.3 Sources of Segregation

Various studies have been conducted on sources of HMA segregation. Each step

in the process of aggregate handling and HMA production, hauling and paving can be a source of segregation. Also, segregation potential can increase or decrease based on the asphalt mixture design. Brock (1986) states that the most important factor related to segregation is properly designing the mix. Kennedy et al. (1986) indicated that asphalt content and gradation are the two mix design factors which significantly affect the tendency for segregation. Mixtures with a large maximum aggregate size, coarse grading or gap grading have a greater tendency to segregate than do finer or well graded mixes (Kennedy et al, 1986). Brock (1986) describes a gap graded mixture as one with a gradation that makes an "S" across the maximum density line. He also states that a gap graded mixture with low asphalt content cannot be produced without segregation.

Proper stockpiling techniques will help ensure that uniform material is being fed to the HMA manufacturing facility. Stockpiles consisting of aggregate particles with differing specific gravity tend to segregate. Particles with higher specific gravities settle during handling, increasing segregation (Elton, 1989).

Stockpiling single sized aggregate minimizes segregation in stockpiles (Elton, 1989). Also, building conical stockpiles with a wide range of sizes should be avoided. The larger particles tend to roll to the outside and bottom of the pile. The problem is more pronounced with large stockpiles (Kennedy et al., 1986). Brock (1986) states that large stockpiles with varying aggregate sizes are prone to segregation.

In the case of drum mix plants, segregated stockpiles cause special problems (Kennedy et al., 1986). He contributes this to the fact that there is no internal gradation check , i.e. hot screening. Since there are no screens as in a batch plant, any segregated

aggregate is fed to the plant and ultimately placed (Kennedy et al., 1986).

Cold feed bin opening configurations can contribute to segregation even if the aggregate is unsegregated in the stockpile. In the cold feed bins, bridging of the aggregate can occur (Kennedy et al., 1986) leading to segregated mixes being fed to the plant. Brock (1986) believes that segregation will not occur at the cold feed bins unless a stockpile with varying sizes is used.

Segregation can also occur in batch plants. The hot bin screens must be kept in good repair. Holes in the screens leads to contamination of the next largest size range (Elton, 1989). The finer screens are sensitive to "blinding". The return of the fines from the bag house may also contribute to segregation as it collects towards the front of the finest bin (Brock, 1986). The finer material can accumulate and surge into the weigh bin.

Drum mixers are also a source of segregation in the HMA manufacturing process. Larger, coarser material tends to travel faster through the drum (Brock, 1986). Steep drum slopes may accentuate the problem of the coarser material traveling faster through the plant. The finer material tends to go higher up the sides of the drum during mixing, which will segregate the mix if the coarse material is traveling faster through the drum (Elton, 1989). Steep drum slopes also increase the potential for segregation since the aggregate dwell time in the drum is decreased, not allowing sufficient time for proper particle coating. Asphalt tends to provide mix cohesion, therefore insufficient aggregate coating may lead to segregation (Kennedy et al., 1986). Gravity discharge of material from the drum on to the conveyor to the storage silo is also a sensitive area for segregation. As the mixture is deposited onto the belt, the coarse material may be

deposited on one side of the belt with the fine material deposited on the other.

The process of conveying HMA to the surge silos can contribute to segregation. A ladder or drag conveyor is generally used to deliver freshly mixed HMA from the drum to the storage silo. Segregation will usually not occur on a drag conveyor unless there is "hydroplaning" or the mix is segregated as it is fed onto the drag conveyor (Brock, 1986). "Hydroplaning" is caused when the drag conveyor is cold and a buildup of fine material occurs on the flights. This buildup will cause the coarse material of fresh HMA to spill backwards down the conveyor rather than move up the conveyor with the fine fraction as a uniform mixture (Brock, 1986).

There are conditions associated with the surge bins or storage silos which may contribute to segregation. One main concern is proper placement of the mix into the silo. This placement can be achieved with a bin loader or batcher, or a rotating chute (Elton, 1989). A bin loader allows mix to accumulate in a bin above the storage silo until it reaches its capacity, then drops the mix into the silo as a batch. A rotating chute is a continuous feed device that keeps the material being fed into the storage silo from collecting in a cone in the middle of the bin. Problems can arise during loading of the storage silo with a rotating chute if the end of the chute wears away. The material entering the silo will have a horizontal trajectory rather than a vertical one and coarse material will collect on the outside of the bin (Kennedy et al., 1986). The amount of material kept in the storage silo can also significantly affect segregation. Kennedy et al. (1986) suggested keeping the silos at least one third full at all times. Brock (1986) also recommends not allowing the material to fall below the top of the bottom cone during bin

discharge.

Truck segregation is likely to occur if the trucks are loaded incorrectly from the storage silo (Brock, 1986). Coarse material will collect towards the outside walls of the truck if the truck is not loaded in distributed batches, i.e. one drop in the front of the truck, one in the back and one in the middle (Kennedy et al., 1986). This segregated material will then be fed directly to the paver resulting in a segregated area between each truck load of material (Kennedy et al., 1986).

Even when material is successfully processed through all of the steps of HMA production segregation can still occur in the HMA paving machine (Brock, 1986). Areas of concern include operation of the paver wings; auger operation including condition and speed; proper flooding of the hopper; truck loading; and proper adjustment of the screed (Kennedy et al., 1986).

2.4 Non-Destructive Measurement of Segregation

Permeability has been used in the past to detect areas of segregation. Zube (1962) showed that dense-graded HMA pavements became highly permeable to water, 1.3 mm/sec, at approximately 8 percent air voids. Above 8 percent air voids, the permeability increases quickly. Brown et al. (1989) in a study of segregated mixes showed that HMA mixtures were impermeable to water as long as the air void content was below approximately 8 percent.

Nuclear gauges have been studied and used as a quality control device in the asphalt industry for many years (Belt et al., 1991). However, most studies have used

nuclear density and asphalt content independent of each other. Nuclear gauges have the advantage of rapidly and non-destructively measuring pavement densities (NAPA, 1991). Duncan (1996) conducted a laboratory study using a nuclear moisture/density gauge and concluded that the gauge can effectively identify variations in asphalt mixture physical properties attributed to segregation. Several researchers have concluded that the nuclear gauge accurately measures density when compared with densities of cores, i.e. Kennedy et al. (1989) and the Missouri Highway and Transportation Department (1991).

Studies using a nuclear gauge to determine asphalt content were performed by Regan (1975) and Christensen and Tarris (1989). Both studies found nuclear gauges to produce results comparable to those of conventional extractions. However, they do warn that the presence of absorbed moisture in aggregate can cause problems as the readings are based on a heavy hydrogen count. The reason is the hydrogen in both water and asphalt, a hydrocarbon, are measured cumulatively.

The State of Georgia proposed a method for using a nuclear density gauge to detect segregation based on density variations between a suspected segregated area and an adjacent unsegregated area. A suspect site on the pavement mat was identified visually. The nuclear gauge in the backscatter mode was used on the surface of the suspect site to determine the uncorrected density. The surface voids were then filled with a fine slurry of water, sand and cement. The slurry was then covered with a plastic sheet of Saran Wrap and the area retested. If the difference between the two readings was greater then 10 pcf, the area was considered segregated. This method has not been utilized by the State of Georgia since a new method was developed. The new method

Georgia has proposed utilizes the nuclear gauges void count as the governing property concerning segregated areas. If a visually segregated pavement area has voids exceeding 9% as determined by the nuclear gauge, then the area is considered suspect and should be removed. This procedure has not been accepted yet due to lack of supporting data to confirm the correlation between in place air voids as determined by the nuclear gauge and degree of segregation.

The State of Montana uses a method that is the same as the Georgia slurry method, except that the density difference allowed is only 6 pcf before sites are considered segregated. The Montana method is outlined in the survey form that was submitted for data contained in Chapter 3 and is contained in Appendix A. The survey form did not state whether the method has been accepted or is currently used in Montana.

Winfrey (1990) proposed a method to detect segregation on coarse areas using the Troxler thin-lift density gauge. The thin lift gauge is supplied with a calibration plate upon which the gauge may be placed to eliminate surface voids error. The gauge was used to take an initial density reading on a visually segregated area of the pavement. The calibration plate was then placed over the coarse area and the gauge placed on top of the plate. The gauge was placed in the surface void mode and a second reading taken. If the measured difference in density between the two readings exceeded 9 pcf, the area was considered segregated. This method was not in place at the time the survey outlined in Chapter 3 was conducted, nor was it recommended by the State itself due to the lack of data for confirmation of the procedure.

Colorado outlined a method to detect segregation with a nuclear density gauge

based on density variations in the pavement mat. The proposed procedure entailed placing the nuclear gauge on a visually identified segregated area and taking a one minute density count. A second density count would then be taken at an adjacent area of the compacted pavement surface. If the density difference between the two readings was more than 5 pcf, then the pavement was considered segregated. The survey form states that the method was seldom tried and never used as a specification.

Cross and Brown (1993) stated that if the nuclear gauge was utilized to determine the unit weight of segregated areas of a pavement, low values will be determined which might be useful in verifying segregation during construction.

Lackey approached the problem by measuring density profiles with nuclear density readings (Lackey,1986). Measured density profiles can be determined along the lane length or across the lane width. By measuring the area to be tested in sublots, i.e. a 12 ft wide paving lane measured at two foot intervals, and comparing the density reading versus distance, a density profile can be developed. As already stated, coarsely segregated areas of pavements have an open texture and low density.

Based on studies and applications in the literature, a nuclear density gauge can be used to measure density differences resulting from segregation as part of construction control. Some state agencies, Kansas and Missouri, utilize the nuclear gauge in this manner to develop a density profile and evaluate the pavement for segregation.

Permittivity is a relatively new technology being applied to the HMA industry. To date, there has only been one study with this technology applied to HMA. This research was conducted by Al-Qadi et al. (1991) on small specimens to measure the

effect of moisture on asphalt concrete at microwave frequencies. They were able to measure moisture content with reasonable accuracy by measuring the dielectric properties of wet and dry specimens. These specimens were tested in a reflection mode, however the specimens were metal-backed. As a result, this technique is not currently viable as a non-destructive field test method.

2.5 Fatigue

Fatigue testing of laboratory prepared HMA specimens is used to estimate the fatigue properties of an asphalt mixture. Subsequently, these properties are used to estimate pavement life for fracture (Epps and Monismith, 1969, Kallas and Puzinauskas, 1972). The test can be conducted in two modes, either constant stress or constant strain. Roberts et al. (1991) report that experience has shown thick asphalt pavements of five inch thickness or greater generally perform close to the constant stress mode of loading while thinner pavements perform close to the constant strain mode of loading. This test is normally used to compare various mixtures and rank them for relative performance as it is impossible to duplicate field conditions.

Epps and Monismith (1969) tested three different gradations of a California 12.5 mm maximum size aggregate mixture. The gradations were the middle, and extreme fine and coarse limits of the grading band. The mixtures were all designed based on a six percent asphalt content which is not typical of varying levels of segregation. They concluded that aggregate grading has little effect on the fatigue relationship that cannot be explained by differences in asphalt or air void content. Further, Epps and Monismith

concluded that the three different levels of gradation were not statistically different and represented the three levels as a single regression line.

Khedaywi and White (1996) developed a laboratory procedure for segregating an optimum mixture. They tested a 25 mm nominal maximum aggregate size gravel mixture at five levels of segregation. The fatigue curves (log ϵ vs. log N_f) of the five levels of segregation were linear and parallel. At a given level of strain, coarser segregated mixtures had lower cycles to failure.

2.6 Laboratory Accelerated Wheel Track Testing

To date, there has been no documented laboratory accelerated testing of segregated mixtures. This is likely the result of wheel track testing being a more recently developed test. The literature reveals that there has been three laboratory accelerated wheel tracking devices used in the United States. They are considerably different in design. These are the Laboratoire Centrale des Ponts et Chaussees (LCPC) French Rutter, the Georgia Loaded Wheel Tester (GLWT) and the Hamburg Steel Wheel Tracking Device (HSWT). Tables 2.1 through 2.3 list the test conditions and parameters for each device. Each device has used different criteria in evaluating mixture performance. The French Rutter's criteria of a quality mix is one that ruts less than 20 percent of the test specimen's thickness (CDOT, 1996). The GLWT's criteria is a rut depth of 7.5 mm for 8000 wheel passes for a poor mix (Collins, 1996). And, the HSWT's criteria is a 4mm rut depth in less than 20,000 wheel passes (Hamburg Road Authority, 1992) for failure. In application of the French Rutter, both rutting and uplift are

measured. The HSWT measures just rutting. Both rutting and uplift are measured during tests with the GLWT. Literature for these wheel track testers indicate inconsistencies in the tests. As a result, testing duplicate samples is recommended and if an inconsistency between two tests do occur, a third sample is tested. No comparisons of equivalency between the different test apparatus has been reported.

Table 2.1 Test Parameters of the LCPC French Rut Tester (Partl et al., 1995 and Colorado Department of Transportation, 1996)

Parameter	Condition
Number of specimens tested simultaneously	Two.
Range of test temperature	35 - 60°C.
Environmental condition	Dry cycle testing only.
Maximum specimen size	Up to 100 × 160 × 500 mm.
Wheel types	Pneumatic only (up to 690 kPa tire pressure).
Wheel size	400 mm diameter, 90 mm wide.
Load	Up to 5000 N.
Frequency of measurement	User designated by setting a mechanical counter after every rut depth measurements.
Rut depth measurement location	Three locations centered ±90 mm about center of specimen.
Method of rut depth measurement	Manually placing "fingers" at new place of measurement.
Acquisition of data	Automatic.
Wheel speed	1.6 m/s.
Wheel wander	Wheel wander is not an option.

Table 2.2 Georgia Loaded Wheel Tester (Lai, 1994)

Parameter	Condition
Number of samples tested simultaneously	Three.
Range of test temperature	40 - 60°C.
Environmental condition	Dry cycle testing only.
Maximum specimen size	Up to 75 × 125 × 300 mm.
Wheel type	Aluminum wheel on a pressurized hose (700 kPa hose pressure).
Wheel size	Not Available.
Load	Up to 445 N.
Frequency of measurement	User designated by setting a mechanical counter after a single rut depth measurement.
Rut depth measurement location	Three locations centered ±50 mm about center of specimen.
Method of rut depth measurement	Manually adjusting a sliding table at place of measurement.
Acquisition of data	Automatic.
Wheel speed	0.6 m/s.
Wheel wander	Wheel wander is not an option.

Table 2.3 Hamburg Steel Wheel Tracking Device (Hamburg Road Authority, 1992)

Parameter	Condition
Number of samples tested simultaneously	Two.
Range of test temperature	50°C.
Environmental condition	Wet cycle testing only.
Maximum specimen size	Up to 175 × 305 × 305 mm.
Wheel types	Steel wheel, 47 mm wide.
Wheel size	203.5 mm.
Load	Up to 697 N.
Frequency of measurement	Every 250 wheel passes.
Rut depth measurement location	Center of specimen.
Method of rut depth measurement	Automatic by linear voltage displacement transducers.
Acquisition of data	Automatic.
Wheel speed	Sinusoidal with a maximum of 0.33 m/s at the center of sample.
Wheel wander	Wheel wander is not an option.

CHAPTER 3. STATE OF PRACTICE AND DEVELOPMENT OF TRAINING VIDEO

3.1 State of Practice

A survey was conducted of the 50 state departments of transportation, plus the District of Columbia, to determine awareness of segregation, specifications or guidelines for its prevention and any test methods for its detection. Survey forms were distributed to the chief materials engineer for each agency. The completed survey forms for each of the state agencies that responded are contained in Appendix A.

Forty-two of the fifty-one agencies (82%) that were sent questionnaires responded. These results were used to establish the knowledge base and significance of factors relating to segregation.

The main areas addressed in the survey were:

1. Agency specifications for prevention or minimization of segregation.
2. Agency training for segregation prevention techniques during production.
3. Methods for detecting or quantifying segregation.
4. Penalties imposed for stripping.
5. Desire for segregation prevention training material.

Results of the survey included:

1. 55% of the agencies responding have specifications or guidelines for the prevention of segregation during production and placement of HMA.
2. 79% of the agencies responding train technicians for procedures that minimize segregation during production and placement of HMA.
3. Of the 83% of the responding states that address segregation through either specifications or training, 57% were specific as to potential sources of segregation which are addressed by their agency. These areas are outlined below with the percentage of those states that specifically address the problem area.
   - A. 26% Mix Design.
   - B. 34% Stockpiling of Aggregate.
   - C. 37% Plant Operations.
   - D. 46% Storage Silos.
   - E. 40% Truck Loading.
   - F. 46% Paving and Laydown.
4. Of the responding agencies, 64% attempt to quantify the degree of segregation when it is known to exist. 7.4% of the agencies that state they quantify segregation were not specific as to their method. Of those states that were specific, the following methods are used:
   - A. 78% Visual evaluation.
   - B. 19% Nuclear gauge to detect either air voids or density variation across the mat.

C. 41% Asphalt extraction and gradation analysis on cores or random HMA samples.

5. No agency responding included a pay reduction factor for stripping.

6. Eighty-six percent of the states responding were very interested in any training material that could be provided to reduce or prevent segregation from occurring.

These results indicate a significant awareness of segregation. The primary effort to address the problem is through training and is therefore preventative. Also, the results show that more emphasis is placed on post mixing HMA segregation.

3.2 Development of Training Video

One of the tasks of the research project was development of a training video. The video is intended to act as a training tool for contractors and government agencies in identifying sources, causes and methods for minimizing HMA segregation. A copy of the video, "Hot Mix Asphalt Segregation " can be obtained through the Joint Highway Research Program by calling (317)494-9310. The script developed for the video is given in Appendix B. The video script was reviewed by industry and government agencies.

CHAPTER 4. CHARACTERIZATION OF LABORATORY PREPARED SPECIMENS

4.1 Introduction

To quantify segregation, data was needed for the characteristics of mixtures with varying levels of segregation. This data would help identify which properties are important in identifying segregation non-destructively.

4.2 Materials

4.2.1 Asphalt and Aggregates

The materials incorporated in this study are commonly used for hot mix asphalt pavements in Indiana. Table 4.1 lists test results for the AC-20 grade asphalt used in the study and the Indiana Department of Transportation (INDOT, 1995) asphalt specifications. Table 4.2 lists aggregate characteristics and sources. Each aggregate source is INDOT approved.

4.2.2 Asphalt Mixtures

Four asphalt mixtures were studied. These included #11 surface mixes, 12.5 mm nominal maximum aggregate size, and #8 binder mixes, 25.0 mm nominal maximum aggregate size as defined by INDOT. Two aggregate types, limestone and gravel aggregate, were utilized. INDOT aggregate specifications require 100 percent of the

particles have one crushed face for high volume surface mixes and a minimum of 95 percent for high volume binder mixes (INDOT, 1995). INDOT also restricts the type of aggregate to slag or limestone.

Mix designs were conducted using a 75 blow Marshall hand-hammer compaction effort. Optimum asphalt contents were selected solely on 6 percent air voids which is INDOT's criteria. Otherwise, the mix design followed the procedure described in the Asphalt Institute Manual, MS-2 (Asphalt Institute, 1995). INDOT mix design criteria includes a minimum stability of 5340 N, and a maximum flow value of 16. Voids in the mineral aggregate requirements are a minimum of 16.0% and 14.0% for the surface and the binder mixes, respectively. Characteristics of the surface and binder mixes are listed in Tables 4.3 and 4.4, respectively. The gradations for the surface mixtures are shown in Figure 4.1 and those for the binder mixtures in Figure 4.2.

4.3 Laboratory Segregation Techniques

Five mixes with varying degrees of segregation were produced for each of the four HMA types. The mixtures designated as the control mix were the result of the Marshall mixture design method outlined in Table 4.3 and Table 4.4. These mixtures were included in the study as one of the five degrees of segregation.

Preparation of segregated mixtures involved mixing the control mix in 2000g batches (see Figure 4.3) at the selected optimum asphalt content. These batches were cured in the oven at the compaction temperature for one hour. The hot mix was then passed over a heated sieve as shown in Figures 4.4-4.7. The resulting fractions were then

placed into pans for further material testing.

The sieves were selected based on the fact that when the heated control mix was passed through the sieve, approximately 50% was retained and 50% passed. These proportions made estimation of material quantities easier. Enough material for each mix was prepared in 2000g batches to provide adequate amounts of segregated material to conduct the asphalt extraction tests and subsequent gradation analysis. This sieving created two fractions of the control mix (refer to Figure 4.8), coarse (retained on the sieve) and fine (passing the sieve). These fractions were used as two degrees of segregation, very coarse and very fine.

Two other mixes were produced with intermediate degrees of segregation by combining differing percentages of the coarse and fine materials. The five mixtures were produced using the percentages of coarse and fine material outlined in Tables 4.5 and 4.6.

Bryant (1968) developed these manual segregation procedures using laboratory prepared surface mixtures. In the study, a procedure was developed to pass fresh hot mix over heated sieves and proportion the resulting fractions to examine varying asphalt content and film thickness with different gradations. This "segregation" was quantified based on gradation and extracted asphalt content. Khedaywi and White (1994) used a similar laboratory procedure to develop the segregated proportions for an Indiana #8 Binder and #11 Surface mixtures.

4.4 Characterization of Segregated Mixtures

Physical properties of laboratory segregated and compacted asphalt mixtures were

determined. These properties established the baseline for measurements with the proposed nondestructive testing equipment. These physical properties included asphalt content, gradation, density and voids.

4.4.1 Segregated Mixture Asphalt Content/Gradation

Extractions (ASTM D 2172 - 92) and sieve analyses (ASTM C 136) were performed on each mixture prepared at the five levels of segregation. Results of the extractions are shown in Table 4.7. The gradations of the segregated limestone #11 surface and #8 binder mixtures are shown in Figures 4.9 and 4.10, respectively. Corresponding gradations of the segregated gravel mixtures are shown in Figures 4.11 and 4.12, respectively. The specific asphalt content and gradation for each level of segregation were used in preparing batches of mixtures for testing.

4.4.2 Density and Air Voids

A target density was required for each segregated mixture to prepare samples for testing. In attempts to compact segregated mixtures with the Marshall hand-hammer, the very coarse mixtures exhibited considerable aggregate crushing and the very fine mixture flushed. In the latter case, material flowed up the sides of the Marshall mold and collar during compaction. As an alternative, samples were compacted in the Gyratory Testing Machine (GTM) using procedures in ASTM D 3387-83.

GTM compaction conditions were 1380 kPa vertical pressure, 1 degree angle of gyration and 30 revolutions. Four samples were prepared for each level of segregation.

Resulting density and air voids based on the GTM compacted samples are given in Tables 4.8 and 4.9, respectively.

4.5 Laboratory Specimens for Non-Destructive Testing

Planned non-destructive tests of the segregated mixtures required that compacted samples be large enough so that the results would not be influenced by sample size. In order that samples meet the size criteria, a linear compactor was designed and fabricated (Brown, K. 1993). The non-destructive tests that were planned included thermal imaging, air permeability, nuclear moisture(asphalt) and density, and permittivity.

4.5.1 Specimen Preparation

In addition to preparing slabs with various levels of segregation for testing, other applications were envisioned for slabs prepared with the linear compactor. These other applications included accelerated wheel track testing and fatigue testing. The critical slab geometry appeared to be the dimensions for testing with a nuclear moisture/density gauge. Plan dimensions adopted were 62.25 cm by 30.5 cm. The maximum thickness was set at 12.7 cm because the moisture/density gauge requires a minimum layer thickness of 12.5 cm to satisfy an assumption of infinite depth for measurement (Brown, K., 1994). Thus, the controlling slab dimensions were 62.25 cm long by 30.5 cm wide by 12.7 cm high. The Purdue Linear Compactor (PLC) is shown in Figure 4.13.

Nuclear gauge application also raised the issue of base pavement type effects (i.e.

asphalt or concrete). Consequently, both types of base layers were incorporated into the tests. In taking this approach, slabs were prepared that would represent the cases of a thin overlay of an asphalt or concrete base. An overlay thickness of 5.1 cm and a base thickness of 7.6 cm were adopted. The asphalt base (control mixture) was prepared at the same time as the segregated overlays. Concrete bases were fabricated in advance. They were allowed to cure for a minimum of 21 days before applying a tack coat and compacting the hot mix asphalt on top.

Two segregated conditions were considered, hidden segregation and visible, surface segregation. Figure 4.14 shows a schematic of samples prepared with hidden segregation. Tables 4.10 and 4.11 show the tests that have been conducted. Factors tested were mix type, aggregate type, control and extreme segregation, and hidden (blind) and visible, surface segregation.

Material for each 2.5 cm of compacted slab was batched and mixed in a Hobart mixer. These batches were placed in a forced draft oven for an hour to allow for asphalt absorption. Mixtures prepared at each level of segregation were compacted in the PLC to the previously determined GTM densities for each level of segregation.

Table 4.1. Asphalt Cement Properties

Asphalt Cement Properties (Amoco AC-20, Whiting, IN)	Test Result	INDOT Specifications, 902.01(g)-93.
Specific Gravity @ 25°C	1.036	N/A
Flash Point (Cleveland), °C	288	232 minimum
Kinematic Viscosity @ 135°C, cSt	393	300 minimum
Absolute Viscosity @ 60°C (300mm Hg vacuum), Poise	2165	1600 - 2500
Penetration @ 25°C, 100g, 5 sec	65	N/A
Loss on Heat (T.F.O.T.)	0.25	99.0 minimum
Viscosity @ 60°C, Poise	5293	8000 maximum
Ductility @ 25°C, 5 cm/min, cm	110	40 minimum
Solubility, %	99.9	50-110

Table 4.2. Aggregate Characteristics

Agg. Nominal Size	25.0mm	12.5mm	4.75mm	25.0mm	12.5mm	4.75mm	
Agg. Type	Crushed Gravel	Crushed Gravel	Man. Sand (Gravel)	Limestone	Limestone	Man. Sand (Lmstn.)	Mineral Filler
Agg. Source	Rogers. Williamsport. IN			Rogers. Kentland. IN		Delphi. IN	Swayzee. IN
Bulk Sp. Gr.	2.6373	2.5694	2.6400	2.6526	2.6553	2.7300	2.7000
Crush Count	100	100	N/A	100	100	N/A	N/A
Sieve Size. mm	Percent Passing						
25.0	100	100	100	100	100	100	100
19.0	92.6	100	100	91.1	100	100	100
12.5	52.1	100	100	62.4	100	100	100
9.5	34.4	71.8	100	30.8	79.8	100	100
4.75	11	10.2	100	0.9	17.0	100	100
2.36	2.8	1.6	77.0	0.0	1.5	89.2	100
1.18	0.0	0.0	47.3	0.0	0.0	59.0	100
0.60	0.0	0.0	30.7	0.0	0.0	41.0	100
0.30	0.0	0.0	19.7	0.0	0.0	25.6	96.6
0.15	0.0	0.0	9.7	0.0	0.0	9.1	71.3
0.075	0.0	0.0	4.3	0.0	0.0	2.1	21.9

Table 4.3. Optimum Surface Mixture Characteristics

Gravel		Limestone	
Aggregate	Percent in Blend	Aggregate	Percent in Blend
12.5mm Crushed Gravel	45.0	12.5mm Limestone	47.0
Man. Sand (Gravel)	53.0	Man. Sand (Lmstn.)	51.0
Mineral Filler	2.0	Mineral Filler	2.0
Combined Agg. Sp. Gr.	2.609	Combined Agg. Sp. Gr.	2.694
Asphalt Mixture Properties		Asphalt Mixture Properties	
Bulk Specific Gravity	2.337	Bulk Specific Gravity	2.393
Stability, N	15575	Stability, N	14685
Flow, 1/100in.	15.5	Flow, 1/100in.	12.3
Air Voids, percent	6.0	Air Voids, percent	6.0
Voids in the Mineral Aggregate, percent	16.0	Voids in the Mineral Aggregate, percent	16.0
Optimum Asphalt Content, percent	6.0[1]	Optimum Asphalt Content, percent	5.5[1]

[1]Based on total weight of mixture.

Table 4.4. Optimum Binder Mixture Characteristics

Gravel		Limestone	
Aggregate	Percent in Blend	Aggregate	Percent in Blend
25.0mm Crushed Gravel	70.0	25.0mm Limestone	62.0
12.5mm Crushed Gravel	0.0	12.5mm Limestone	8.0
Man. Sand (Gravel)	28.0	Man. Sand (Lmstn.)	28.0
Mineral Filler	2.0	Mineral Filler	2.0
Combined Agg. Sp. Gr.	2.639	Combined Agg. Sp. Gr.	2.675
Asphalt Mixture Properties		Asphalt Mixture Properties	
Bulk Specific Gravity	2.364	Bulk Specific Gravity	2.404
Stability, N	13350	Stability, N	12460
Flow, 1/100in.	15.1	Flow, 1/100in.	14.8
Air Voids, percent	6.0	Air Voids, percent	6.0
Voids in the Mineral Aggregate, percent	15.2	Voids in the Mineral Aggregate, percent	14.1
Optimum Asphalt Content, percent	5.0[1]	Optimum Asphalt Content, percent	4.3[1]

[1]Based on total weight of mixture.

Table 4.5 Segregation Proportions for Surface Mixtures

Mix Designation	Segregation Classification	+ 4.75 mm Material (%)	- 4.75 mm Material (%)
Mix No. 1 (M1)	Very Fine	0.0	100.0
Mix No. 2 (M2)	Fine	18.0	82.0
Mix No. 3 (M3)	Control (Mix Design)	As Mixed	
Mix No. 4 (M4)	Coarse	68.0	32.0
Mix No. 5 (M5)	Very Coarse	100.0	0.0
Percentages were determined in accordance with Khedaywi and White (1994).			

Table 4.6 Segregation Proportions for Binder Mixtures

Mix Designation	Segregation Classification	+ 9.5 mm Material (%)	- 9.5 mm Material (%)
Mix No. 1 (M1)	Very Fine	0.0	100.0
Mix No. 2 (M2)	Fine	24.0	76.0
Mix No. 3 (M3)	Control (Mix Design)	As Mixed	
Mix No. 4 (M4)	Coarse	76.0	24.0
Mix No. 5 (M5)	Very Coarse	100.0	0.0
Percentages were determined in accordance with Khedaywi and White (1994).			

Table 4.7 Segregated Mixture Asphalt Contents

	Mix			
Segregation Level	Surface, Gravel (%)	Surface, Limestone (%)	Binder, Gravel (%)	Binder, Limestone (%)
Very Fine	8.3	7.2	7.7	6.7
Fine	7.5	6.5	6.2	5.6
Control	6.0	5.5	5.0	4.3
Coarse	5.2	4.8	3.5	3.0
Very Coarse	3.8	3.8	2.2	2.1

Table 4.8 Segregated Mixture Gyratory Density, Bulk Specific Gravity

	Mix			
Segregation Level	Surface, Gravel (%)	Surface, Limestone (%)	Binder, Gravel (%)	Binder, Limestone (%)
Very Fine	2.227	2.342	2.267	2.437
Fine	2.256	2.362	2.267	2.418
Control	2.278	2.354	2.250	2.285
Coarse	2.253	2.328	2.117	2.173
Very Coarse	2.112	2.158	1.930	1.978

Table 4.9 Segregated Mixture Air Voids

	Mix			
Segregation Level	Surface, Gravel (%)	Surface, Limestone (%)	Binder, Gravel (%)	Binder, Limestone (%)
Very Fine	7.71	6.50	5.83	1.63
Fine	7.54	6.05	8.08	3.73
Control	8.56	6.65	10.88	10.36
Coarse	10.47	8.82	17.73	16.04
Very Coarse	17.94	16.30	26.67	24.51

Table 4.10 Surface Mixture Design of Experiment

	Level of Segregation		
Sample Configuration	Very Fine	Control	Very Coarse
Asphalt Base (7.5cm)			
-5cm Surface	G G	G G	G G
- 2.5cm Blind	G G L L	G G L L	G G L L
Concrete Base			
- 5cm Surface	G G	G G	G G
- 2.5cm Blind	G G L L	G G L L	G G L L

* G = Gravel, L = Limestone

Table 4.11 Binder Mixture Design of Experiment

	Level of Segregation		
Sample Configuration	Very Fine	Control	Very Coarse
Asphalt Base (7.5cm) -5cm Surface - 2.5cm Blind	G G L L	G G L L	G G L L
Concrete Base - 5cm Surface - 2.5cm Blind	G G L L	G G L L	G G L L

* G = Gravel, L = Limestone

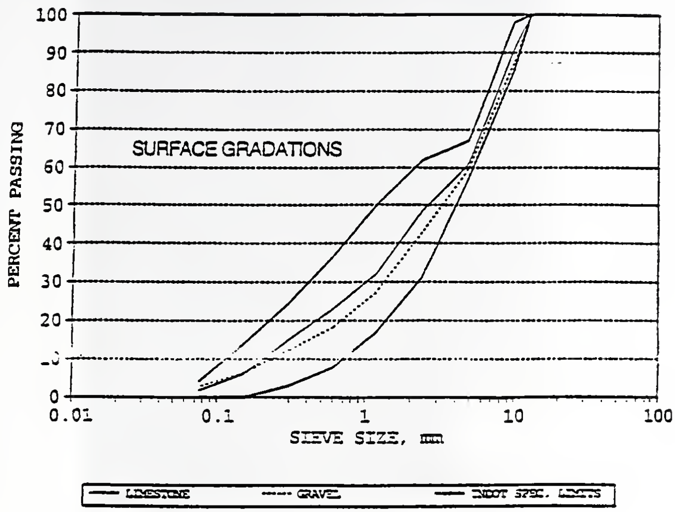

Figure 4.1. Surface Mixture Gradations

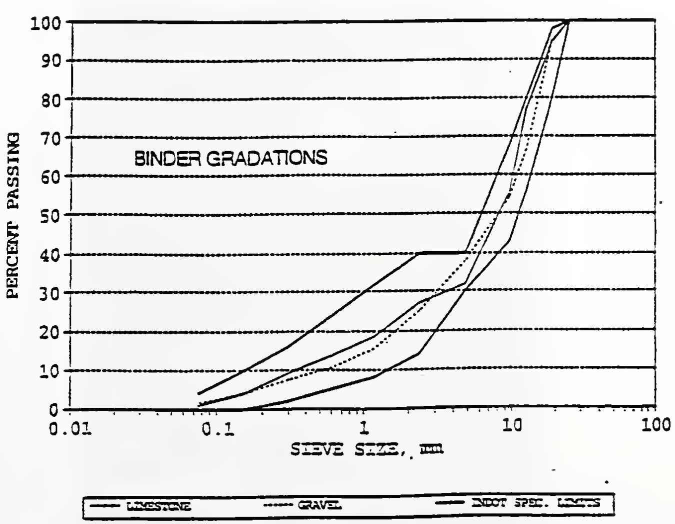

Figure 4.2 Binder Mixture Gradations

Figure 4.3 Mixing 2000 g of Control Mix

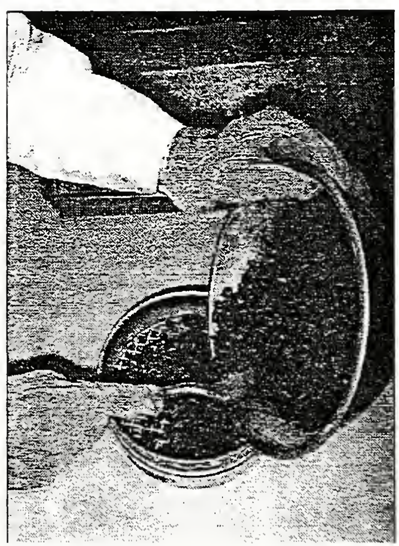

Figure 4.4 Transferring Control Mix to Sieve

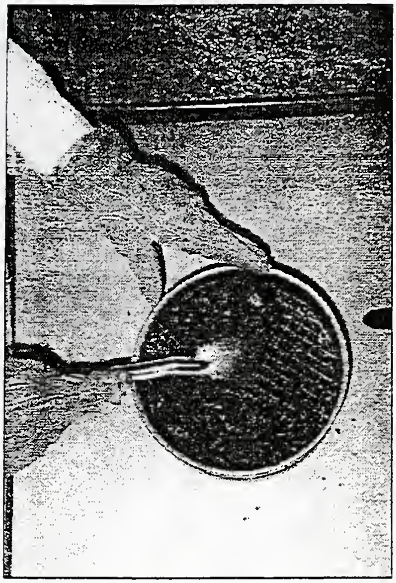

Figure 4.5 Segregating Hot Mix Over Sieve

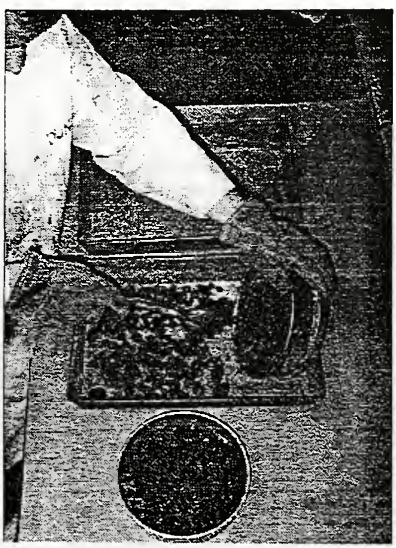

Figure 4.6 Transferring Coarse Fraction to Pan

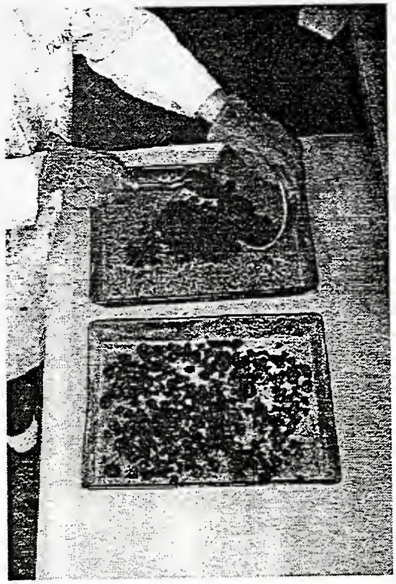

Figure 4.7 Transferring Fine Fraction to Pan

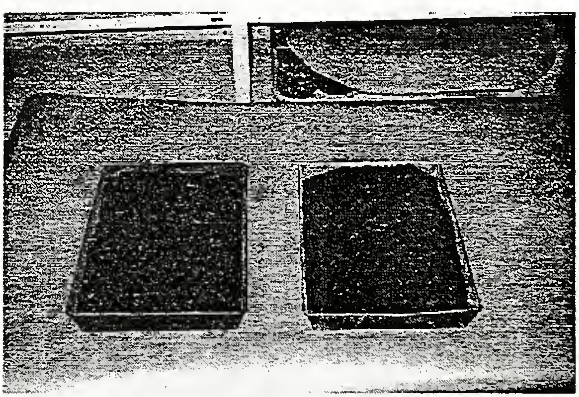

Figure 4.8 Resulting Fractions from Segregation Sieving

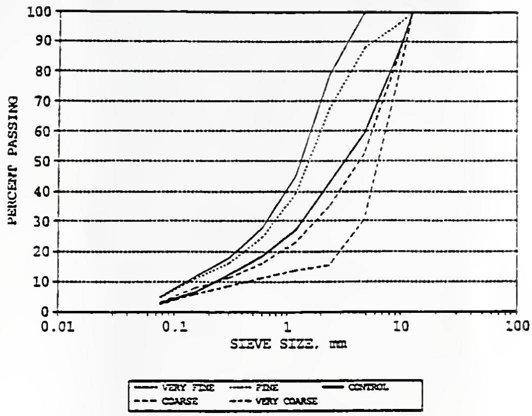

Figure 4.9 Segregated Gravel Surface Mixture Gradations

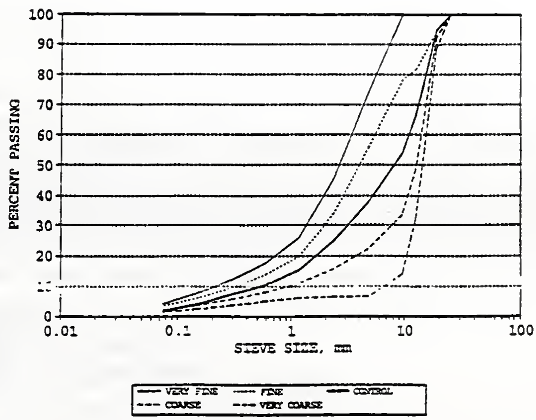

Figure 4.10 Segregated Gravel Binder Mixture Gradations

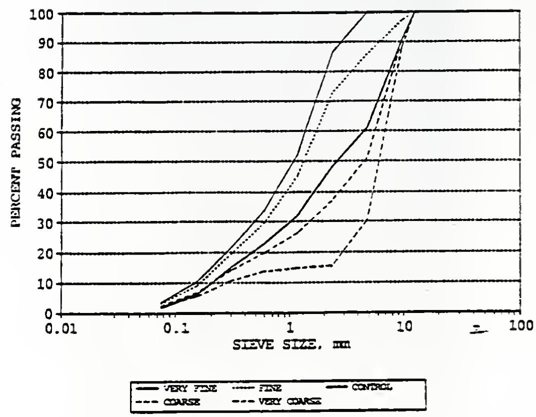

Figure 4.11 Segregated Limestone Surface Mixture Gradations

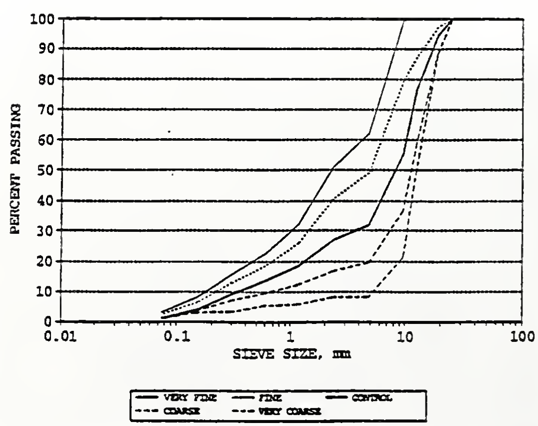

Figure 4.12 Segregated Limestone Binder Mixture Gradations

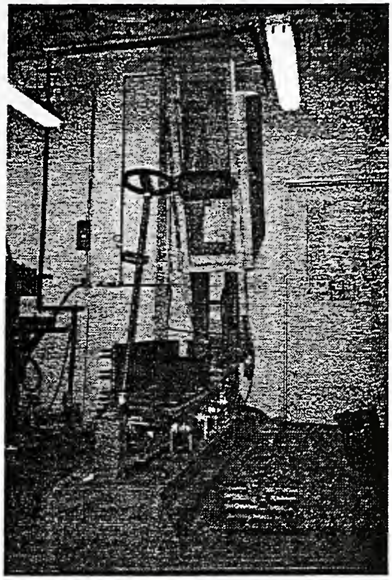

Figure 4.13 Purdue Linear Compactor (PLC)

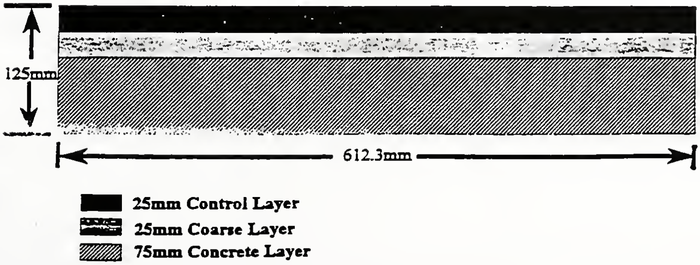

Figure 4.14 Schematic of Hidden Segregation

CHAPTER 5. NON-DESTRUCTIVE TESTING FOR SEGREGATION

5.1 Introduction

One objective of this study was to identify technologies for detecting segregation. Detection implies that one or a combination of physical characteristics could be measured and subsequently correlated with degree of segregation. Technologies considered were: 1. thermal imaging, 2. air/water permeability, 3. nuclear moisture(asphalt) and density, and 4. permittivity.

5.2 Thermal Imaging

Thermal imaging equipment was field tested on an existing pavement, at a hot mix asphalt plant, and at a paving project to determine its overall effectiveness in detecting segregation. The basis for using this equipment was that different size aggregates would retain or gain heat at different rates. In general, thermal imaging did confirm locations of segregated areas that were visually identified. However, the technology was not considered effective in locating segregation occurring beneath the surface.

5.3 Water or Air Permeability

Zube (1962) and Brown, et al (1989) conducted water permeability tests to detect

segregation. Both concluded that as the air void level exceeded eight percent, the permeability increased significantly. In the significance section in ASTM D 3637-84 (1995), it is pointed out that full saturation is more easily obtained with air as the medium as opposed to water. Lower pressure is implied which reduces risk of turbulent flow. Potential for volume change is also reduced.

Permeability (air or water) in application to asphalt mixtures is a measure of connected air voids. Connected air voids would increase with mixture segregation. As a result, permeability would potentially correlate with level of segregation. It was decided to try measuring air permeability first. The basis for this decision was that if tests with air permeability were not successful, then water permeability would not be either.

The air permeameter used for testing laboratory samples is shown in Figure 5.1. Each sample was tested four times (ASTM D 3637-84, 1989) and the results averaged. The air permeability for the surface mixtures with surface and blind segregation are shown in Figures 5.2 and 5.3 and Figures 5.4 through 5.11, respectively. The air permeameter does not differentiate between the very fine and control levels of segregation, but does show a difference between the control and very coarse levels of segregation as indicated in Figures 5.2 and 5.3. The air permeameter was not successful in detecting blind segregation, as indicated in Figures 5.4 through 5.11. In summary, the air permeameter can satisfactorily identify coarse, surface segregation.

5.4 Moisture/Density Nuclear Gauge

Pavement density has and is being used as an indicator of segregation. In a study

for the Georgia DOT (Brown et al, 1989) used nuclear density to indicate segregation as part of construction quality control. Cross and Brown (1993) used a thin lift nuclear gauge to measure densities in areas visually identified as segregated.

Careful consideration of the principles on which the nuclear gauge operates suggests that the nuclear moisture/density gauge can be used to measure asphalt content. The moisture reading is independent of the density measurement as there are two different sources, and thus the measurements are not correlated with each other (Troxler, 1993). When moisture measurements are made, the "count" depends on the heavy hydrogen atoms. Asphalt is a hydrocarbon material and therefore the asphalt hydrogen atoms could be "counted" by the nuclear gauge. It is also recognized that the pavement would have to be in a dry condition for the asphalt content reading.

Consequently, tests were conducted using the nuclear gauge to measure both density and asphalt (moisture) content of laboratory compacted slabs prepared with different levels and location of segregation. The nuclear moisture/density gauge and a test slab are shown in Figure 5.12.

5.4.1 Calibration

Nuclear density calibration is conducted using blocks of three different materials. These blocks consist of magnesium, aluminum and a laminated aluminum and magnesium. The aluminum and magnesium blocks represent two extremes in density, 110 and 170 pcf, respectively. A midpoint density is achieved with the laminated block of aluminum and magnesium.

Two blocks are used for moisture content calibration, magnesium and polyethylene. The magnesium block represents zero moisture content and the polyethylene block represents an infinite volume of water because of the high number of hydrogen atoms. The gauge calibration is a straight line between these two extremes. Four minute counts are used for calibrating the gauges (K. Brown, 1995).

A standard count should be taken before use to check gauge operation and allow for source decay (Troxler, 1988). For the particular gauge used in this study, the gauge automatically compares the new count to the average of the last four standard counts. The new count will "pass" if it is within two percent of the moisture average and/or one percent of the density average of the previous four counts. The Manual of Operation and Instruction (Troxler, 1988) should be consulted to ensure safe operating procedures.

5.4.2 Moisture (Asphalt) Content and Density

For this study, the gauge was operated in the soils backscatter modes. The gauge contains two radioactive sources. Cesium-137 is used to measure density and is located within a rod on the left side of the gauge. Americium-241:Beryllium is used for moisture measurement and is located inside the gauge near the center of the base.

5.4.3 Test Procedure Discussion

The number of readings taken with the nuclear gauge was four one minute readings. Belt et al., (1991), concluded that a minimum of four density readings taken for each density measurement and averaged provided very good to excellent final density

values. The Missouri Highway and Transportation Department (1991) study concluded that the possible variation of a single, one minute nuclear gauge reading is unacceptable. They recommended averaging multiple readings to produce a more favorable comparison to actual density. Troxler, during a phone conversation, recommended an average of four one minute reading to provide accurate results. They stated that the running average of four readings was common practice in the field.

A sensitivity study was conducted for the nuclear gauge used in this study. One minute readings were taken on a single sample and a running average of the readings was kept of successive density readings. The asymptotic limit was identified as to where the number of readings ceased to influence the average reading. This limit was achieved between four and six readings. Figure 5.13 presents the results of the sensitivity study. ASTM recommends taking one reading at each test site in the standard testing method. The number of readings taken in this study exceed this minimum amount and should be considered an appropriate number of readings to provide adequate repeatability.

Variability of the moisture and density measurements was also examined for the one and four minute readings on laboratory prepared specimens. The specimens consisted of hidden segregation on two types of base pavements, hot mix asphalt and concrete. The results are shown in Table 5.1 and 5.2 for asphalt and concrete base pavements, respectively. Variability in the moisture and density readings are less for the four minute reading than the one minute reading.

Ten measurements were taken around the perimeter of the slab samples to obtain an average height which was divided into the sample weight to obtain a bulk density.

Habermann (1994) used this procedure to obtain the bulk density of the slabs he fabricated with the PLC.

The measured density was used to produce a basis for comparison to establish appropriate correction factors based on the material properties and sample configurations. These measured densities were used as the basis for density correction factors.

This data also provided a means to measure the effectiveness of the PLC in compaction of HMA. The control mix, full depth slabs could be used in this analysis, assuming uniform compaction throughout the depth of the sample. The segregated samples prevented an estimate of percent compaction obtained with the PLC due to the fact that the density was not uniform throughout the sample (as is the case also with the concrete base slabs). The percent compaction obtained with the PLC when comparing measured densities to target densities from Table 4.8 averaged 96.1 percent compaction given in Table 5.3. The results show that the PLC is an effective compaction device that can produce compactive efforts equivalent to those experienced in the field.

5.4.4 Correction Factors

ASTM D 2950-91 states that it is necessary to establish a density correction factor based on each project. Belt et.al, (1991) also recommended the establishment of density correction factors for each paving project. Kennedy et.al, (1989) stated that density calibration factors are necessary for each project to provide acceptable results.

ASTM D 4125-83 recommends the development of a calibration curve for correction of nuclear asphalt contents. Regan (1975) recommended the establishment of

a nuclear calibration curve over a range of asphalt contents.

Belt et al., (1991) stated that variations in the nuclear gauge density results can be reduced by utilizing user provided inputs. He stated that these variations are caused by variables that are inherent in the pavement mat. The variables that could affect nuclear gauge readings include chemical composition of the material being tested, size and geometry of the aggregate and density variations in the asphalt mix.

A bias analysis was conducted of the nuclear moisture/density gauge results to identify the need for establishment of correction factors for the results of this study. This analysis served to identify any bias caused by main level effects. Main level effects are those independent factors that were varied as a part of this study. These factors include mixture type, base pavement and degree of segregation. The analysis was conducted by plotting the nuclear gauge results against the known material properties which were used as the basis for establishing correction factors. Figures 5.14 - 5.21 contain the plots of this analysis.

In the analysis, a “least squares” linear regression was performed on the data for each mix type and compared to the “optimum fit line”. The optimum fit line is the line that represents perfect accuracy between nuclear gauge readings and the known material properties used for calibration.

The nuclear gauge density readings for the #11 Surface and #8 Binder mixtures, presented in Figures 5.14 and 5.16, show little or no bias from degree of segregation or base pavement. The results suggest that these mixes would require no density calibration for these main level effects.

The nuclear density readings for the #11 Limestone and #8 Limestone, presented in Figures 5.15 and 5.17, do show bias from either degree of segregation or base pavement. As a result, the bias analysis on these mixes was extended to also analyze the bias effect due to differing base pavements. The resulting regression lines show a distinct bias caused by base pavement on the limestone mixes. The main level effects on the limestone mix density results are discussed further in Section 5.4.5.

When comparing the gravel mixes to the limestone mixes, it is apparent that there could be a bias caused by aggregate type. The limestone mixes exhibit a large disparity between nuclear gauge results and the known densities when compared to the gravel mixes. The plots also show that the nuclear gauge overpredicts density for both limestone mixes, regardless of base pavement. This bias is not unexpected based on factory calibration of the nuclear gauge as discussed in Section 5.4.5.

The bias analysis plots for nuclear asphalt content based on each mix are presented in Figures 5.18 - 5.21. The bias analysis of the nuclear asphalt contents allows statements to be made concerning the effect degree of segregation has on the results. Degree of segregation in this study is marked by controlled variations in the as-mixed asphalt content. The data groupings in all of the asphalt content bias plots inherently show the levels of segregation for each mix type. If the regression lines are not parallel with the optimum fit lines, one could state that these biases are caused by variations in the asphalt percentage due to degree of segregation.

The bias analysis for each mix was extended to confirm any bias effects due to base pavement. The results of the extended analysis show that the regression lines divide

the data into two distinct groups. These groups are defined as having either asphalt or concrete bases.

By comparing the nuclear asphalt content bias plots of all of the mixes, one can state that bias is caused by both aggregate type, mix type, base pavement and degree of segregation. One may also state that the nuclear gauge overpredicts asphalt content. All of the bias statements concerning nuclear asphalt content are further discussed in Section 5.4.6.

By correcting for the main level effects identified in the bias analysis, it may be possible to minimize their effect on the nuclear gauges precision. This correction may also reduce the apparent variability of the nuclear gauge results. Consequently, the gauges may then be utilized to generate data which could be used to accurately classify the results into degree of segregation.

The common practice for the establishment of density correction factors is to take nuclear density readings on a pavement and correlate those readings with cores taken from each of the testing locations. Correction for asphalt content readings can be obtained by correlation between readings and extracted asphalt percentages. Since this study was conducted in the laboratory, the known material properties were used as the basis for the correction factors. The process followed in this study for establishing correction factors was as follows:

1. Take four, one minute readings on each sample and or test site
2. Average the four readings.
3. Compare average readings to known material properties.

4. Establish correction factor for each sample and or test site.
5. Analyze the correction factors based upon the independent factors of the study, which include, aggregate and mix type, degree of segregation and base pavement.
6. Establish a standard correction factor based on each of these independent factors at a 95% confidence interval.

The correction factors used in this study for density and asphalt contents are given in Tables 5.4 and 5.5. These correction factors were established based on the process discussed in Appendix C. The analysis of the correction factors based on the independent factors of the study is discussed in sections 5.4.5 and 5.4.6. The output of the analysis concerning the independent factors of the study is contained in Appendix C.

5.4.5 Nuclear Density

The bias analysis conducted in Section 5.2.3 served to identify potential main level effects that could result in erroneous nuclear density readings. The correction factors established for nuclear density in this study were analyzed statistically to further identify and understand the independent variables to which the nuclear gauge were most sensitive. Establishment of these correction factors is critical to accounting for the variations inherent in the gauges sensitivity to certain properties of the materials being tested. By addressing these variations through correction factors, their effect in the classification process could be eliminated. As a result, the possibility of misclassification

based on erroneous readings due to the effect of material properties could be reduced.

Independent variables in the analysis were Degree of Segregation (DOS), Mixture Type (MIXTYPE) and Base Pavement (BSEPAV), each having 3, 4, and 2 levels respectively. The dependent variable was nuclear density.

The General Linear Models (GLM) procedure used in SAS was used for the correction factor analysis. Output from the GLM analysis of the nuclear density correction factors is presented in Appendix C. The analysis indicated that DOS had no effect on the nuclear gauge readings for density. This finding is positive since DOS will not be able to be preestablished in the field. The analysis also showed that BSEPAV and MIXTYPE were significant to the GLM model. These will be either be known or can be tested for to preestablish correction factors for field application of this method.

The MIXTYPE variable included both asphalt mixture types (#11 Surface and #8 Binder) and aggregate types (Gravel and Limestone). It is expected that MIXTYPE would be significant based on how the nuclear gauge is calibrated in the factory.

The density calibration method used at the factory consists of the accumulation of count rate data on five standard density blocks and then on a standard density block to verify calibration accuracy. The accumulation of data on the various calibration blocks provides count rate results for varied densities. These results can then be used in computations of density versus count rate to establish a calibration for a wide range of densities (Troxler Users Manual). Of the five calibration blocks, two are non-metallic and are used for the soil calibration. The two standard blocks are granite and limestone. The assumption is that the density of most soils will fall between the density of these two

limits. So, a calibration with these two materials as the limits will provide a calibration suitable for all normal soils. The other three standard density blocks are metallic and are used to provide data for other factors in Troxler's calibration model (Troxler Users Manual).

By acknowledging this calibration process, one can expect that MIXTYPE would be a significant factor since one of the aggregates in the study is limestone and is on the outside range of the gauge calibration. In a phone conversation with Troxler, they agreed that the limestone mixes would require larger correction factors and be significant due to the factory calibration. The calibration places limestone on the lower limit, meaning it has a lower count rate. This lower count rate would result in a higher density reading, as the results show. The correction factor required lowers the density reading, meaning the gauge overpredicted the density on the limestone samples.

Table 5.4 presents a finding concerning MIXTYPE and its two components, mixture and aggregate type. It can be seen that aggregate type had a larger effect on the nuclear gauge density readings than mixture type. The gravel and limestone mixtures required different correction factors, but the #11 Surface to #8 Binder comparison showed similar correction factors for each aggregate type.

The GLM analysis also concluded that BSEPAV was a significant factor to the density model at a 95% confidence interval. This sensitivity to base pavement was found to be true only for the limestone mixes.

It should be noted that the varied results due to the two base pavements may not be totally attributable to the fact that the samples had different base materials. Effects

due to the thickness of the asphalt layer, although not clearly identified in this study, could prove to be a factor in the gauges precision. The differing base samples in the study had different depths of compacted asphalt. The concrete base samples had a two inch asphalt lift, while the full depth asphalt slabs had a five inch asphalt lift. These different thicknesses of the asphalt layer could be found to have an effect on the gauge readings.

Table 5.4 outlines the density correction factors used for the samples in this study. Figures 5.22 to 5.29 show the plots of the corrected density readings for both asphalt and concrete base samples. The figures show that the nuclear gauge was effective in detecting the density trend for segregated mixtures, which decreases from fine to coarse mixtures. The results also agree with the results of the Cross and Brown study (1993) which concluded that coarsely segregated areas will have lower unit weight values when measured with the nuclear gauge.

The results also show that, in general, the segregated sample density results fell below the 95% minimum density line required by INDOT in field compaction. These low density samples with segregated areas would be unacceptable since they are below the minimum acceptable density. The results show that the nuclear gauge is effective in identifying density variations that would be unacceptable from a quality control standpoint.

5.4.6 Nuclear Asphalt Content Discussion

The bias analysis conducted in Section 5.4.4 served to identify potential main level effects that could result in erroneous nuclear asphalt content readings. Correction

factors established for nuclear asphalt content results in this study were analyzed statistically using the SAS GLM procedure. The GLM analysis identified independent variables suspected of having the largest effect on the nuclear gauge readings of asphalt content. The GLM analysis also served to further understand the main level effects that were causing any identified bias. Output from the GLM analysis of the nuclear asphalt content correction factors is presented in Appendix C.

Independent variables were DOS, MIXTYPE and BSEPAV. The dependent variable was asphalt content. DOS, MIXTYPE and BSEPAV were all found to be significant to the GLM model for the nuclear gauge asphalt readings. This finding shows that the nuclear gauge readings are very sensitive to physical property variations in the mix when it is used to determine asphalt content. ASTM D 4125-83 states that the asphalt content reading is sensitive to aggregate type, source and percentage of asphalt and mix gradation. The standard supports the findings of the GLM analysis and recommends the establishment of correction curves based on the resulting asphalt percentages obtained for each job mix.

Even though the analysis showed that the asphalt content correction factors varied with base pavement, it should be noted that these varied results may not be totally attributable to the fact that the samples had different base materials. The different thicknesses of the asphalt layers in this study may have an effect on the asphalt content readings.

A significant finding of the analysis was that the asphalt correction factors were affected by DOS. Since the asphalt content results varied based on DOS, it can be stated

that the nuclear gauge moisture reading is sensitive to the amount of asphalt in the mix. This statement is supported by ASTM D 4125-83.

This finding is significant since DOS is the only factor in this study that can not be accounted for in the field. If it was determined that the nuclear gauge was sensitive to DOS for certain mixes, it would be necessary to correct for this factor, since DOS will be unknown in the field. MIXTYPE and BASEPAV would be preestablished based on the job mix and job conditions.

Trends from the corrected asphalt content readings match well with the trends obtained through extractions run on very coarse and very fine segregated mixes, which are presented in Figure 5.30. Even though the segregated layer is being tested along with a uniform layer, the segregation effect on asphalt content variation is still evident through the corrected readings.

Table 5.5 shows the correction factors used in this study for each of the various samples. The correction factors vary more than the density factors since the asphalt content test is more sensitive to material properties. Figures 5.31 To 5.38 show the corrected nuclear asphalt content readings for each of the sample configurations. The figures also show that the fine and coarse segregated sample readings are out of the acceptable range for asphalt percentage variation.

Kandhal et al., (1978) stated that the presence of absorbed moisture in the aggregate can cause problems in nuclear gauge readings since the hydrogen in the water is read as additional asphalt. It is understood that the testing must be conducted in the dry condition.

5.4.7 Classification Procedure

A procedure called discriminant analysis was used in this study to classify the data from the nuclear gauge density and asphalt content readings into one of the three degrees of segregation (very coarse, control, very fine). This procedure was used since the discriminant analysis is well suited for a set of observations that contains one or more quantitative variables and one or more classification variables defining groups of observations. The discriminant analysis develops a discriminant criterion to classify each observation into one of the classification groups (James, 1985). Badaruddin et al., (1994) used this method of analysis to identify distress potential in bituminous mixtures at the mix design stage of HMA production.

Discriminant analysis allows a simultaneous consideration of both asphalt content and density variation (two independent readings) in classifying samples into the three degrees of segregation. All of the data obtained through the nuclear gauge testing portion of this study was used in the analysis. The corrected density and asphalt content readings were used in this analysis, since they had been corrected for variations in the nuclear gauge readings due to the effect of DOS, BSEPAV and MIXTYPE on the results. The data consisted of two sets (surface mixtures and binder mixtures) of 24 observations with 2 variables (nuclear density and asphalt content) and three classes (three degrees of segregation - very coarse, control, and very fine). The analysis was separated into two sets since there was significant misclassification with a combined analysis. The analysis had better results when the analysis was conducted separately based on MIXTYPE , surface and binder.

The discriminant analysis uses the method of Generalized Squared distance given in equation 1. This equation can be used to classify any observation into one of the three degrees of segregation distinguished in this study using the classification rule in equation 2.

$$D^2(X_j) = (X-X_j)^T COV^{-1}(X-X_j) \qquad (1)$$

Where,

$D^2(X_j)$ = Generalized Squared Distance from X to group j.

X = Sample Vector (Individual reading considered for classification)

X_j = Sample Mean Vector (Other readings already classified)

COV^{-1} = Pooled Covariance Matrix

T = Transpose of a matrix

Observation X will be assigned to group j if,

$$D^2(X_j) = \min(D_1^2, D_2^2, D_3^2) \qquad (2)$$

Results of the discriminant analysis are contained in Appendix D. Classification and resubstitution information for each of the data sets is contained in Tables D.6 and D.7 and Tables F.13 and F.14.

The analysis did not provide a zero error classification. Zero error classification would be achieved if all of the data were classified correctly into their respective degrees of segregation. Three observations were misclassified for the surface mixtures as shown

in Table D.7. One observation was misclassified for the binder mixtures as shown in Table D.14. The sample population from this study was invariably small and more data may be needed to calibrate the model.

5.5 Permittivity

Permittivity was another candidate technology that was used to test the laboratory prepared segregated mixtures. The hypothesis for use of this technology was based on the assumption that every material has a unique set of electrical characteristics that are dependent on its dielectric properties. The dielectric properties that were examined were resistivity and permittivity. These properties are not constant and change with temperature, orientation, pressure and molecular structure of the material being measured. Resistivity is a DC-resistance measurement of a material. High resistivity is an important characteristic for insulating materials, while low resistivity is important for conducting materials. A material is dielectric if it has the ability to store energy when exposed to an external electric field.

5.5.1 Permittivity Theory

Permittivity, E, describes the interaction of a material with an electric field. The dielectric constant, k*, is equivalent to relative permittivity, $E_r^* = E^*/E_o$. Permittivity consists of real and imaginary components. This relationship can be described as follows:

$$E_r^* = k^* = E^*/E_o = (E'/E_o) - j(E''/E_o) \qquad (1)$$

where:

E_r^* = complex relative permittivity

E_o = permittivity in free space

E_r' = real part of permittivity

E_r'' = imaginary part of permittivity.

The real part of permittivity is a measure of how much energy from an external electric field is stored in a material and is always greater than one for most solids and liquids. The imaginary part of permittivity is also called the loss factor, and it is a measure of dissipativeness of a material when exposed to an external electric field. It is always greater than zero, but is usually much smaller than the real portion. The loss factor includes the effects of both dielectric loss and conductivity.

A system for measuring permittivity includes a vector network analyzer, a coaxial probe apparatus, an external computer and software. The system is based on the network analyzer providing the high frequency stimulus and measures the reflected response. A vector network analyzer consists of a signal source, a receiver and display. The source sends a signal at a frequency to the material being tested. The receiver is tuned to the transmitted frequency to detect the reflected and transmitted signals from the material. The measured response produces the magnitude and phase data at the source transmitted frequency. Subsequently, the input frequency is increased and the measurement repeated. Software is then used to convert the measured data to permittivity, real and imaginary. Relative permittivity values for some common materials are shown in Table 5.6.

5.5.2 Laboratory Measurement of Permittivity

Six gravel samples, three surface and three binder, were prepared using the Purdue Linear Compactor. The samples for both types of mixtures included very coarse, control (no segregation) and very fine mixtures. Permittivity of the six segregated mixtures was measured using the test configuration shown in Figure 5.39. Measurements were performed by Damaskos, Incorporated, Concordville, PA because of the uniqueness of the test equipment.

Measurements were made using a Hewlett Packard 8510B vector network analyzer and Damaskos, Inc.'s propriety Inverted Arch. As indicated, the measurements were made in a direct transmission mode over an input frequency range of 2 to 18 Ghz using Damaskos' Arch Software. Using the transmission coefficients illustrated in Figures 4.40 through 4.51, the dielectric constants of the six samples were computed as a function of frequency. Figures 4.52 through 4.57 reveal that there is a clear difference in the imaginary part of the dielectric constant for the three different levels of segregation for each mix type. However, multiple samples of the same mixture at different levels of segregation were not tested to statistically confirm this difference.

Table 5.1 Mean and Standard Deviation of Five Readings with Nuclear Gauge for Asphalt Base Samples

		One Minute Reading		Four Minute Reading	
Level of Segregation	Sample	Mean, Standard Deviation of Density (pcf)	Mean, Standard Deviation of Asp. (Moist.) Content (%)	Mean, Standard Deviation of Density (pcf)	Mean, Standard Deviation of Asp. (Moist.) Content (%)
Very Fine	11gm1a2	135.30, 0.26	5.96, 0.11	135.28, 0.08	5.80, 0.16
	11gm1b2	135.96, 0.14	3.56, 0.17	135.24, 0.09	3.60, 0.10
Control	11gm3a2	146.06, 0.40	4.72, 0.13	146.76, 0.08	4.58, 0.08
	11gm3b2	145.90, 0.17	4.80, 0.12	145.84, 0.11	4.68, 0.04
Very Coarse	11gm5a2	127.78, 0.16	3.86, 0.24	127.56, 0.08	3.86, 0.24
	11gm5b2	135.96, 0.14	3.56, 0.17	135.24, 0.09	3.60, 0.10

Table 5.2 Mean and Standard Deviation of Five Readings with Nuclear Gauge for Concrete Base Samples

		One Minute Reading		Four Minute Reading	
Level of Segregation	Sample	Mean, Standard Deviation of Density (pcf)	Mean, Standard Deviation of Asp. (Moist.) Content (%)	Mean, Standard Deviation of Density (pcf)	Mean, Standard Deviation of Asp. (Moist.) Content (%)
Very Fine	11gm1a2	140.84, 0.24	5.78, 0.19	140.36, 0.11	5.86, 0.09
	11gm1b2	141.40, 0.18	6.22, 0.13	141.4, 0.06	6.08, 0.11
Control	11gm3a2	139.24, 0.26	6.68, 0.08	139.02, 0.12	4.96, 0.11
	11gm3b2	149.24, 0.16	4.22, 0.16	149.24, 0.09	4.30, 0.07
Very Coarse	11gm5a2	135.90, 0.18	3.54, 0.15	136.20, 0.12	3.58, 0.04
	11gm5b2	129.90, 0.05	3.72, 0.15	130.00, 0.03	3.76, 0.05

Table 5.3 PLC Compaction Ranges

	Percent Compaction		Average
Sample	A	B	
#11 Gravel	95.4	96.3	95.9
#11 Limestone	96.1	95.6	95.9
#8 Gravel	94.9	95.3	95.1
#8 Limestone	97.0	98.2	97.6
		Total Average	96.1

Table 5.4 Density Correction Factors

	Correction Factors - Density							
Mix Type	#11 Gravel		#8 Gravel		#11 Limestone		#8 Limestone	
Base Pavement	AC	CONC	AC	CONC	AC	CONC	AC	CONC
M1	1.002	1.002	1.002	1.002	0.954	0.988	0.954	1.002
M3	1.002	1.002	1.002	1.002	0.954	0.988	0.954	1.002
M5	1.002	1.002	1.002	1.002	0.954	0.988	0.954	1.002

Table 5.5 Asphalt Content Correction Factors

	Correction Factors - Asphalt Content							
Mix Type	#11 Gravel		#8 Gravel		#11 Limestone		#8 Limestone	
Base Pavement	AC	CONC	AC	CONC	AC	CONC	AC	CONC
M1	0.952	0.952	1.175	0.825	0.862	0.952	0.975	0.775
M3	0.952	0.952	1.175	0.825	0.862	0.952	0.848	0.648
M5	0.952	0.952	0.995	0.645	0.862	0.952	0.848	0.648

Table 5.6 Values of Permittivity of Some Common Materials

Material	E_r
Glass	6-10
Mica	6
Porcelain	6-7
Water	80-83
Oil	2-2.2
Air	1.0006

Figure 5.1 Air Permeameter

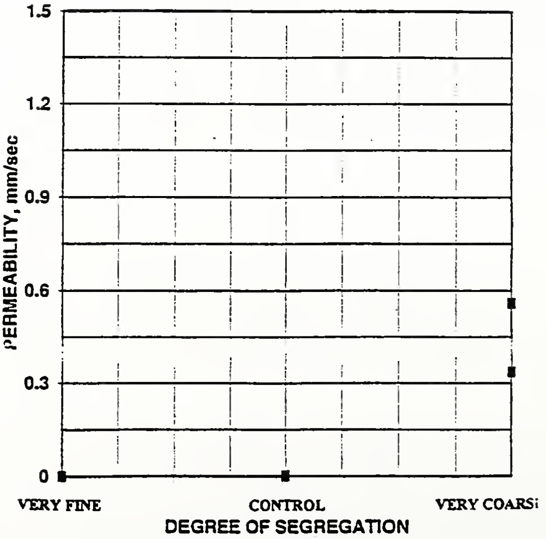

Figure 5.2 Permeability: #11 Surface Gravel, 50 mm Surface Segregation, Asphalt Base

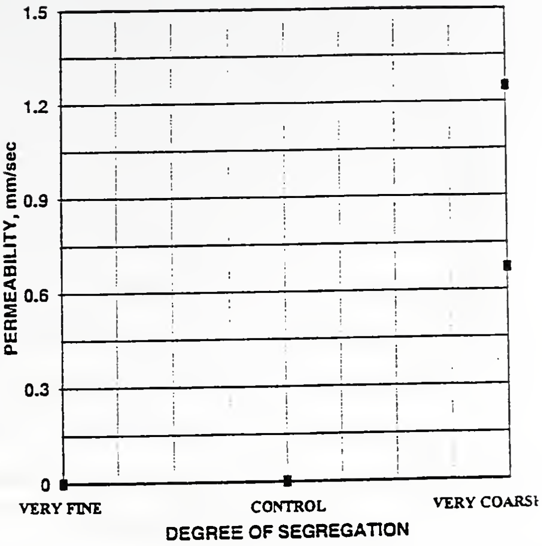

Figure 5.3 Permeability: #11 Surface Gravel, 50 mm Surface Segregation, Concrete Base

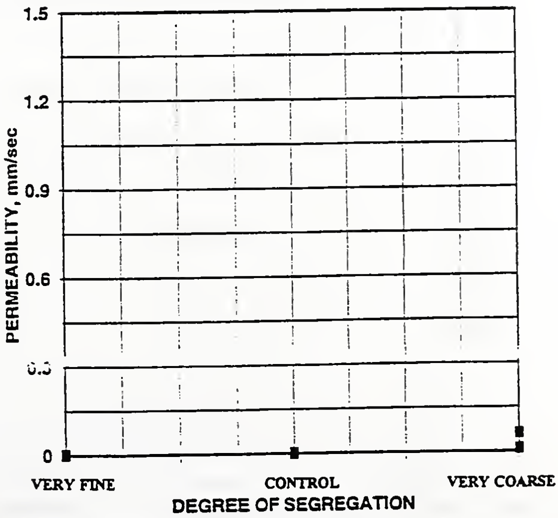

Figure 5.4 Permeability: #11 Surface Gravel, Hidden Segregation, Asphalt Base

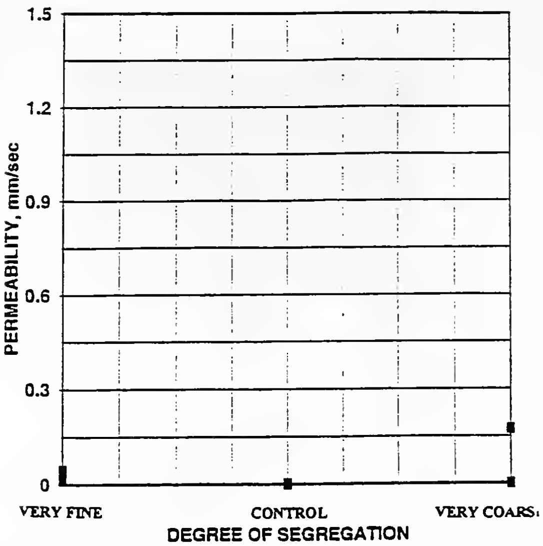

Figure 5.5 Permeability: #11 Surface Gravel, Hidden Segregation, Concrete Base

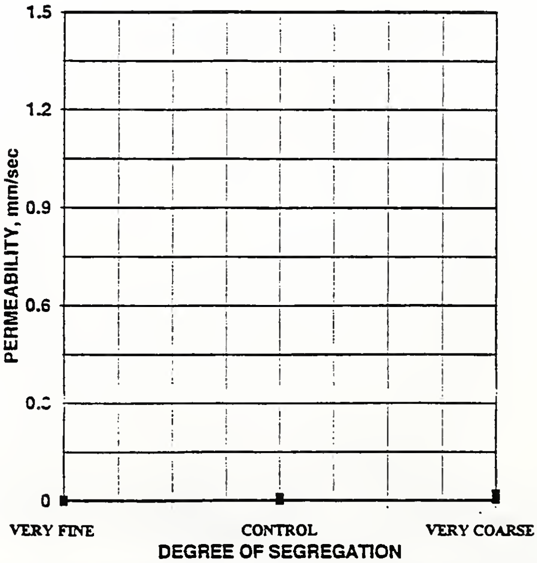

Figure 5.6 Permeability: #11 Surface Limestone, Hidden Segregation, Asphalt Base

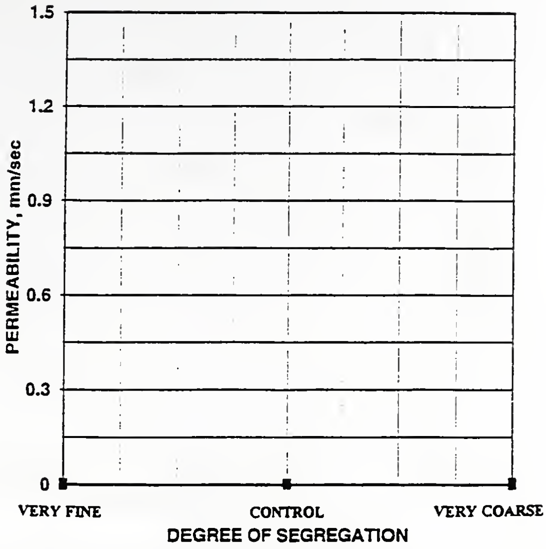

Figure 5.7 Permeability: #11 Surface Limestone, Hidden Segregation, Concrete Base

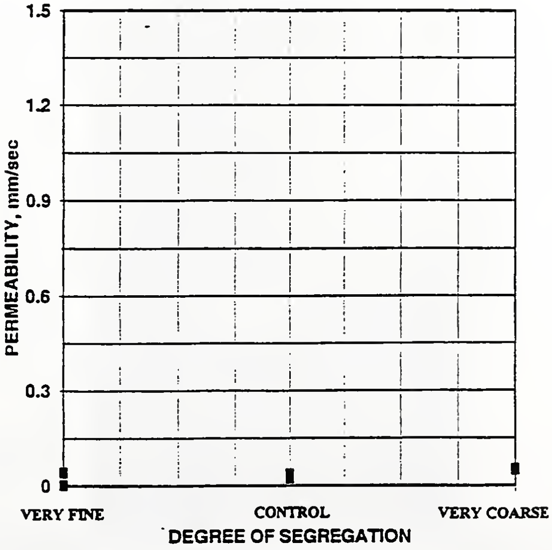

Figure 5.8 Permeability: #8 Binder Gravel, Hidden Segregation, Asphalt Base

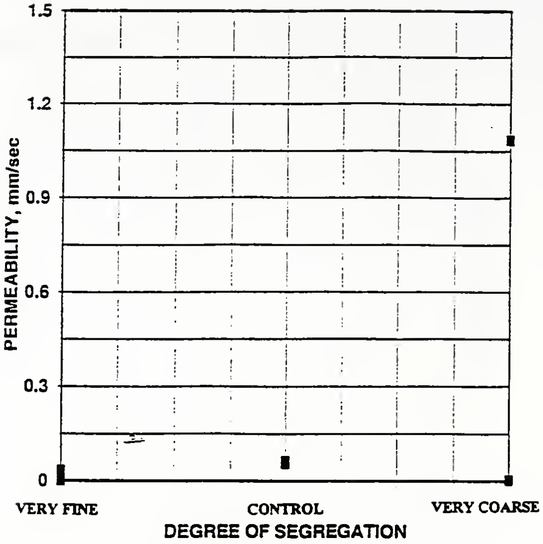

Figure 5.9 Permeability: #8 Binder Gravel, Hidden Segregation, Concrete Base

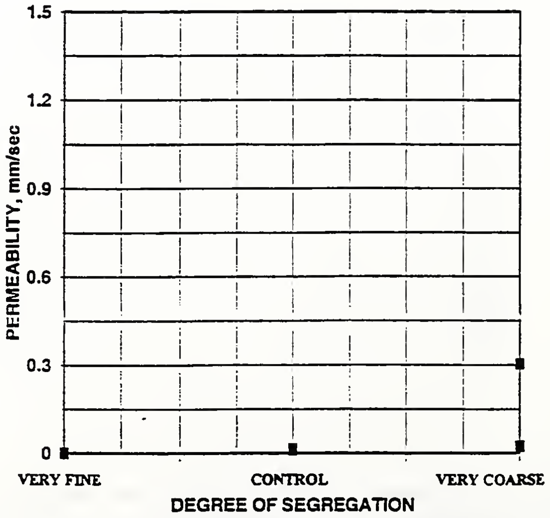

Figure 5.10 Permeability: #8 Binder Limestone, Hidden Segregation, Asphalt Base

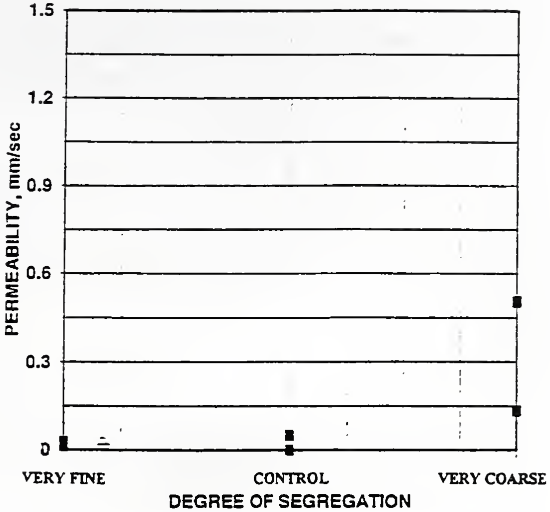

Figure 5.11 Permeability: #8 Binder Limestone, Hidden Segregation, Concrete Base

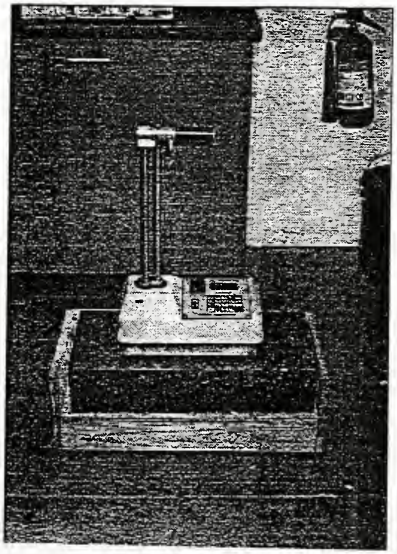

Figure 5.12 Nuclear Gauge

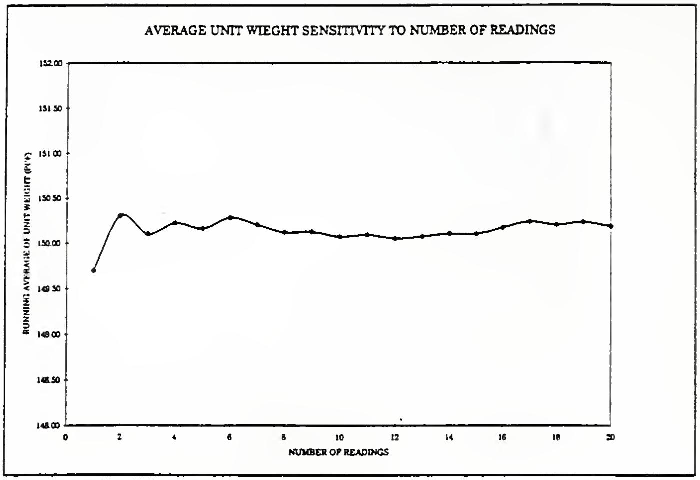

Figure 5.13 Nuclear Gauge Number of Readings

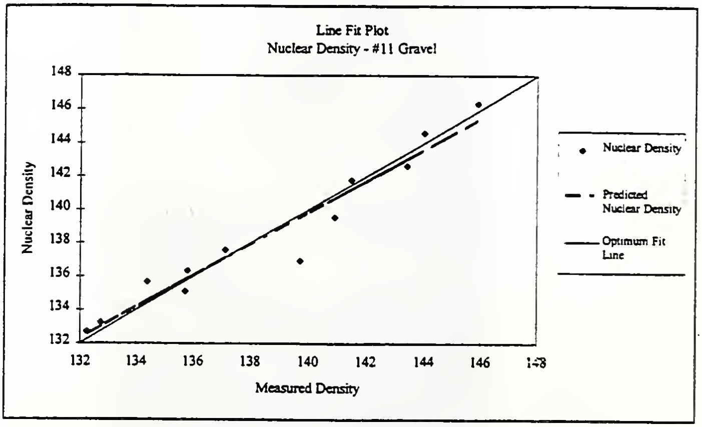

Figure 5.14 Nuclear Density Bias Plot - #11 Gravel

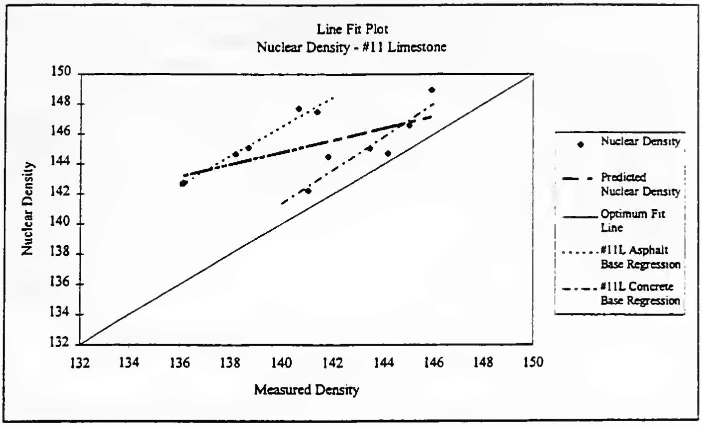

Figure 5.15 Nuclear Density Bias Plot - #11 Limestone

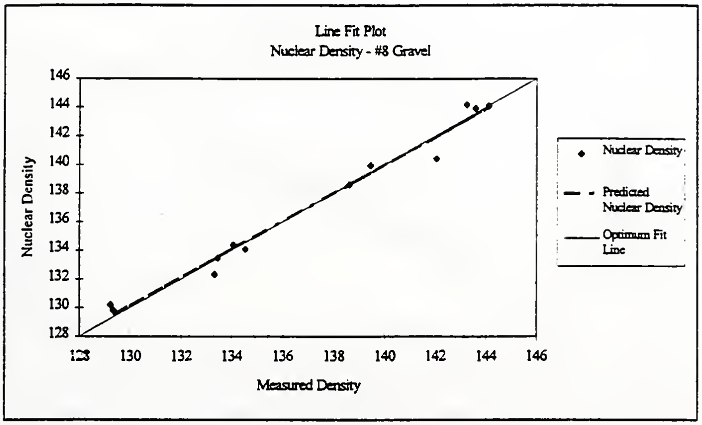

Figure 5.16 Nuclear Density Bias Plot - #8 Gravel

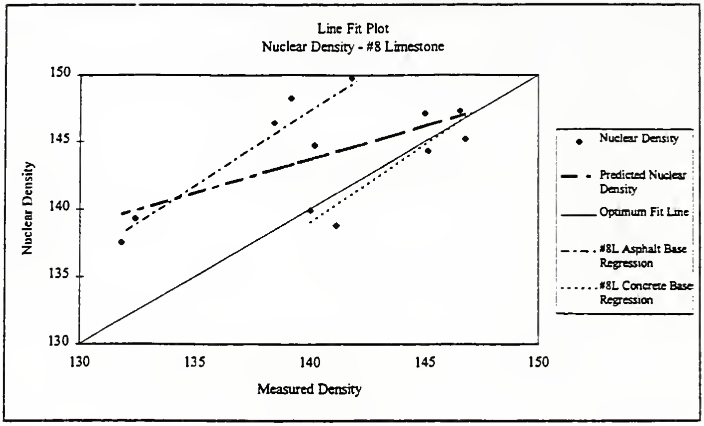

Figure 5.17 Nuclear Density Bias Plot - #8 Limestone

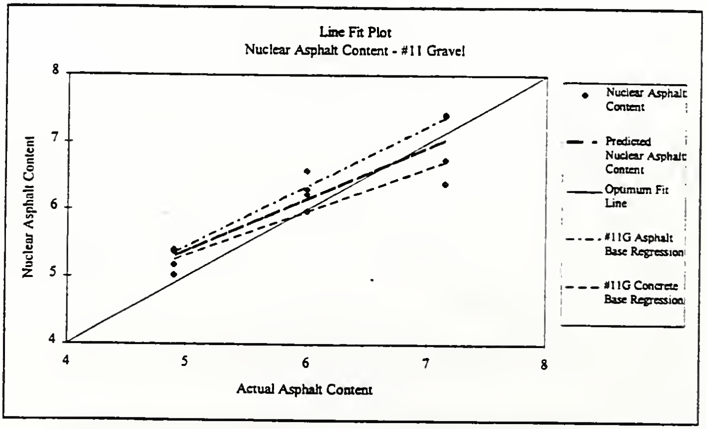

Figure 5.18 Nuclear Asphalt Content Bias Plot - #11 Gravel

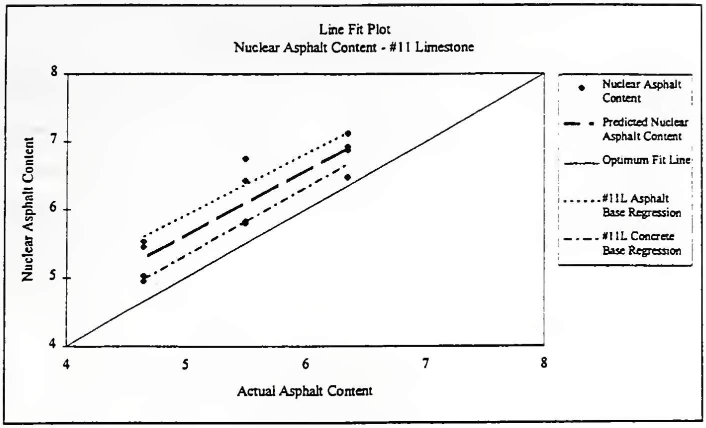

Figure 5.19 Nuclear Asphalt Content Bias Plot - #11 Limestone

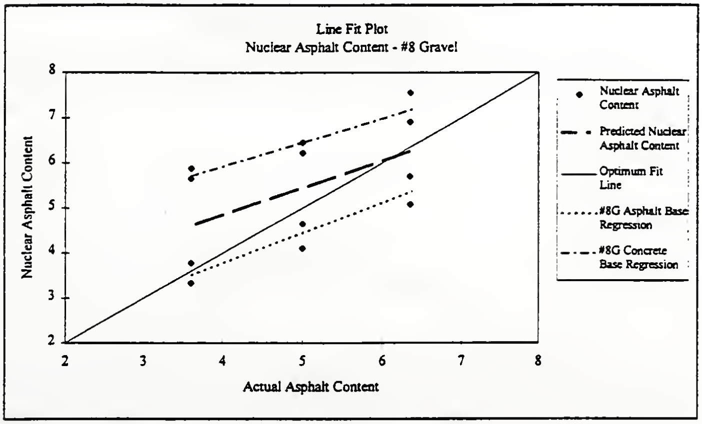

Figure 5.20 Nuclear Asphalt Content Bias Plot - #8 Gravel

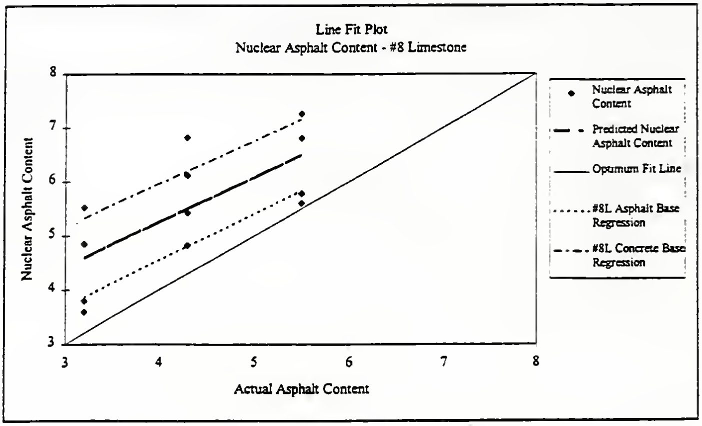

Figure 5.21 Nuclear Asphalt Content Bias Plot - #8 Limestone

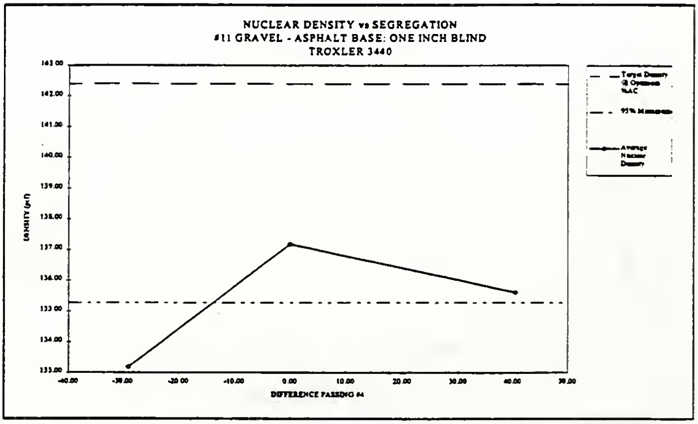

Figure 5.22 Nuclear Density - Asphalt Base - #11 Gravel

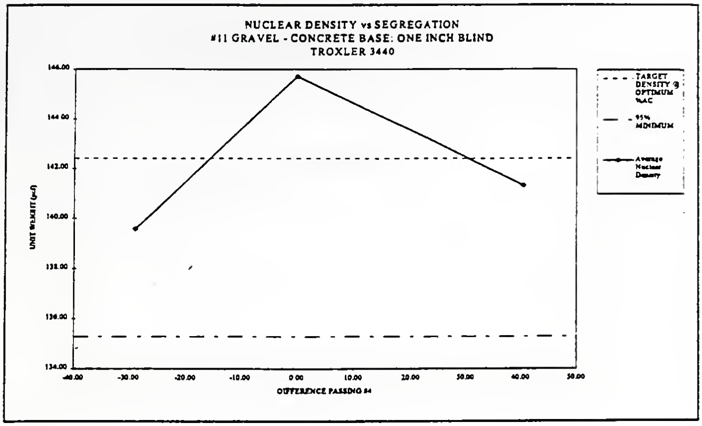

Figure 5.23 Nuclear Density - Concrete Base - #11 Gravel

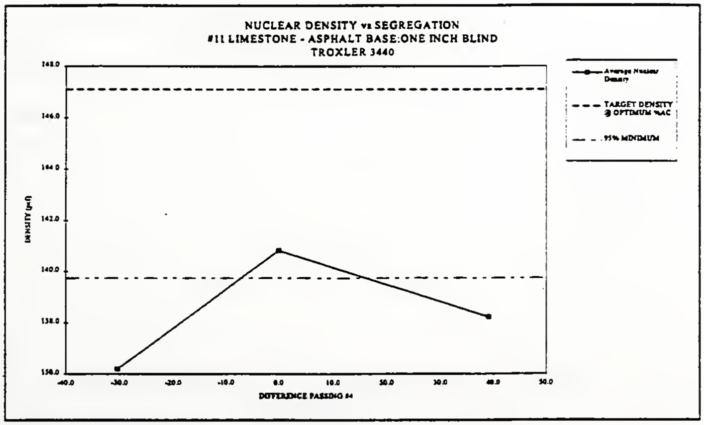

Figure 5.24 Nuclear Density - Asphalt Base - #11 Limestone

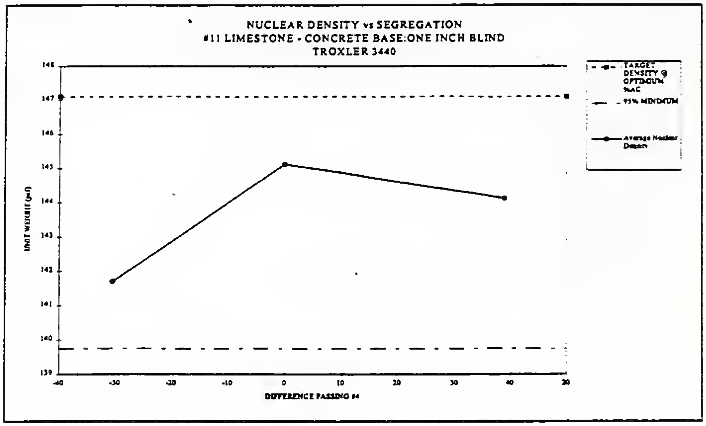

Figure 5.25 Nuclear Density - Concrete Base - #11 Limestone

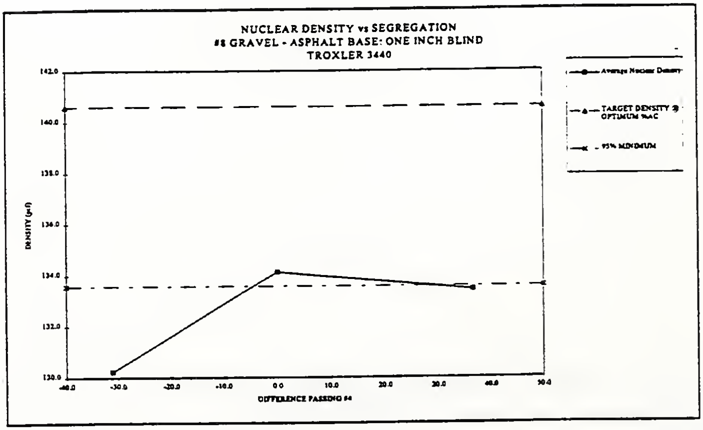

Figure 5.26 Nuclear Density - Asphalt Base - #8 Gravel

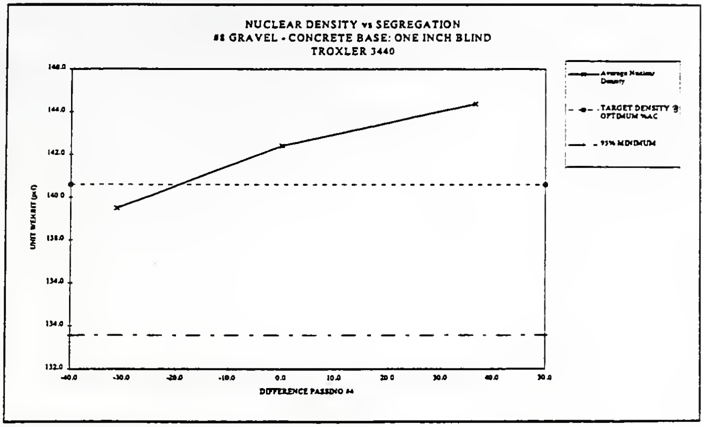

Figure 5.27 Nuclear Density - Concrete Base - #8 Gravel

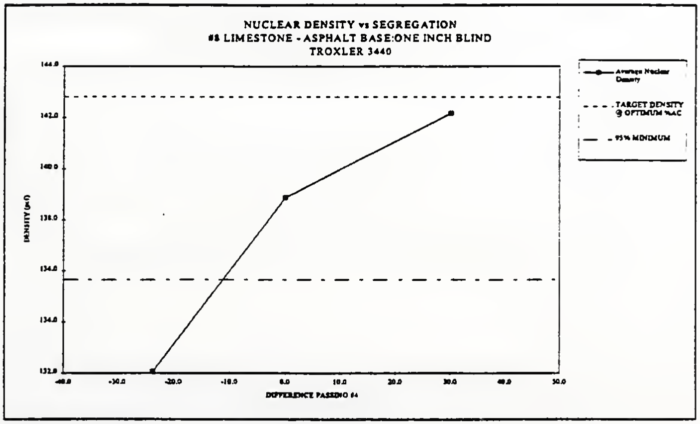

Figure 5.28 Nuclear Density - Asphalt Base - #8 Limestone

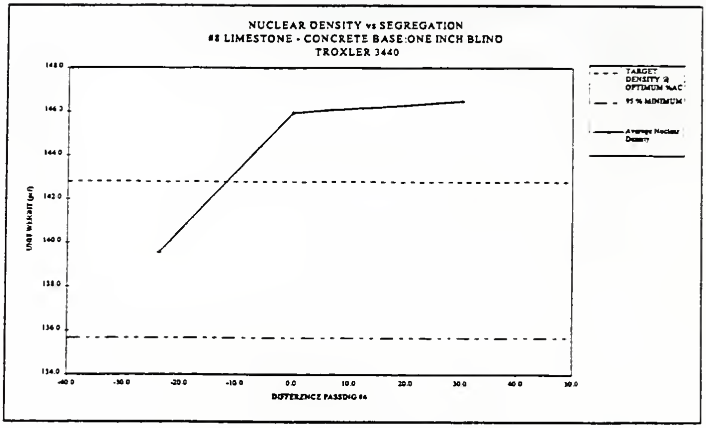

Figure 5.29 Nuclear Density - Concrete Base - #8 Limestone

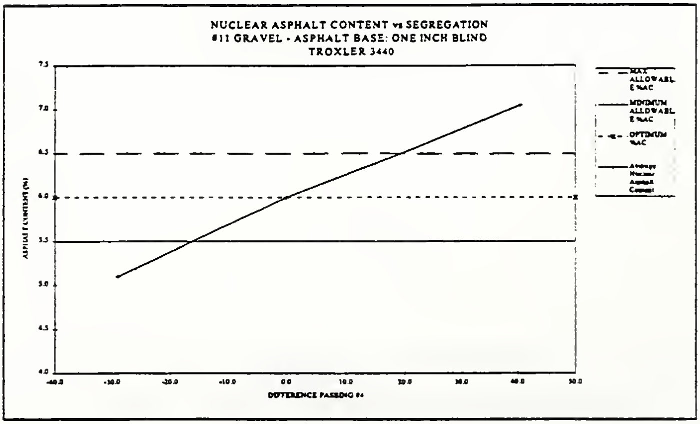

Figure 5.30 Nuclear Asphalt Content - Asphalt Base - #11 Gravel

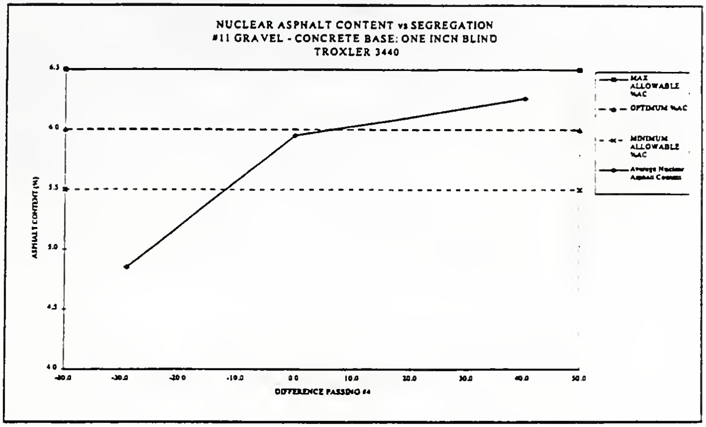

Figure 5.31 Nuclear Asphalt Content - Concrete Base - #11 Gravel

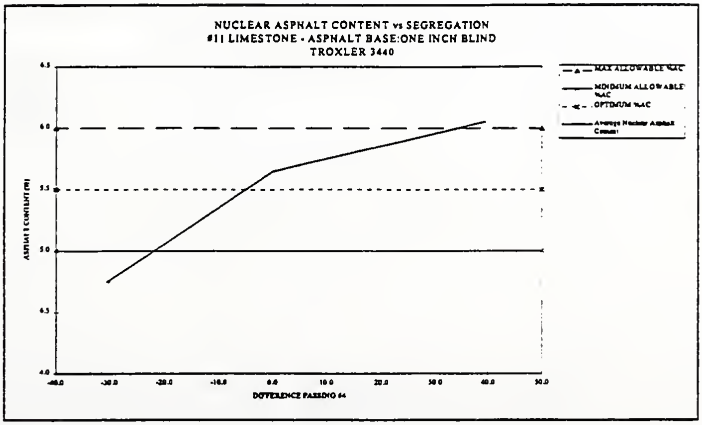

Figure 5.32 Nuclear Asphalt Content - Asphalt Base - #11 Limestone

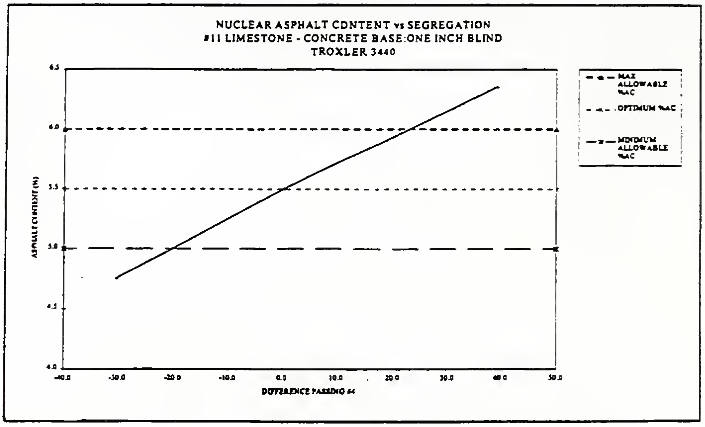

Figure 5.33 Nuclear Asphalt Content - Concrete Base - #11 Limestone

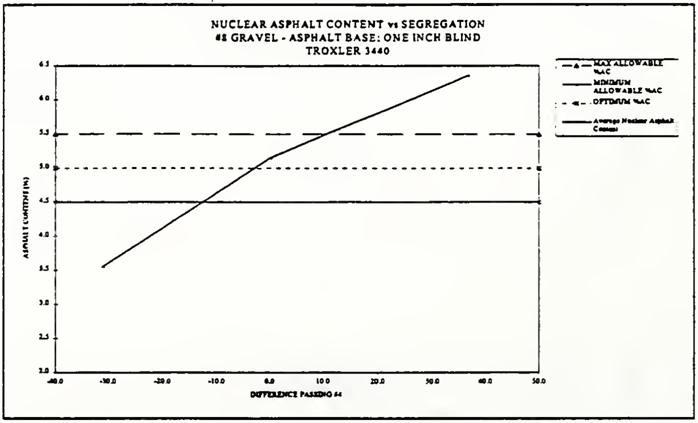

Figure 5.34 Nuclear Asphalt Content - Asphalt Base - #8 Gravel

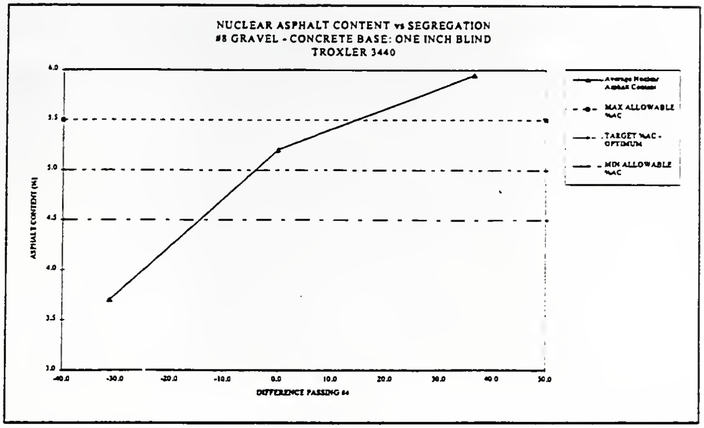

Figure 8.35 Nuclear Asphalt Content - Concrete Base - #8 Gravel

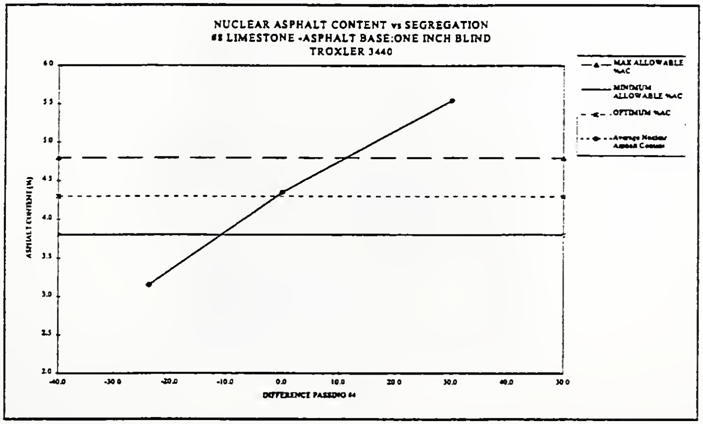

Figure 5.36 Nuclear Asphalt Content - Asphalt Base - #8 Limestone

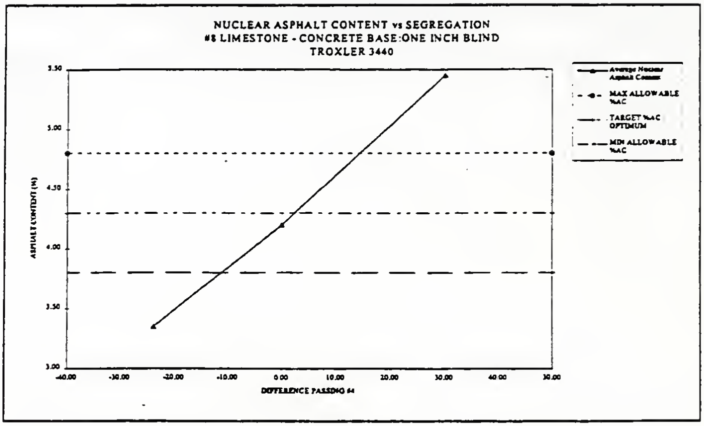

Figure 5.37 Nuclear Asphalt Content - Concrete Base - #8 Limestone

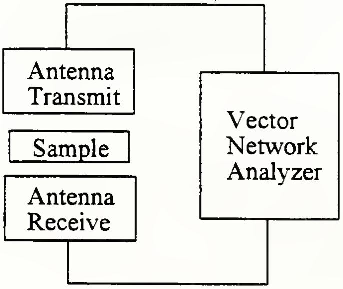

Figure 5.38 Laboratory Dielectric Constant Measurement Equipment

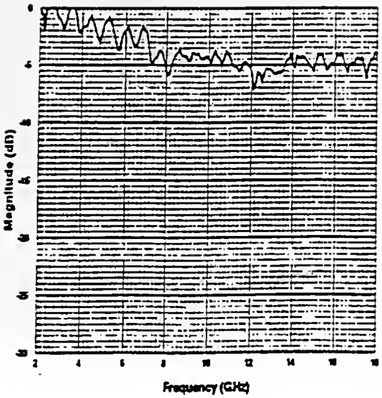

Figure 5.39 Frequency vs. Magnitude Transmission Coefficients, #11 Surface Gravel, Very Fine

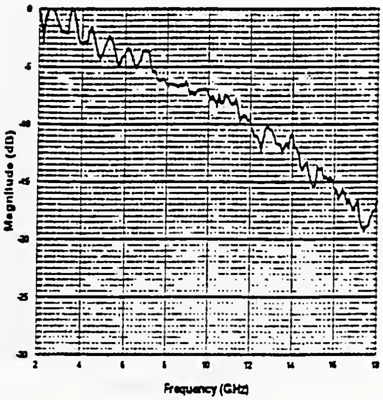

Figure 5.40 Frequency vs. Magnitude Transmission Coefficients, #11 Surface Gravel, Control

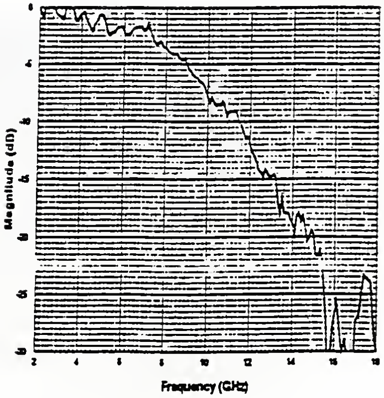

Figure 5.41 Frequency vs. Magnitude Transmission Coefficients, #11 Surface Gravel, Very Coarse

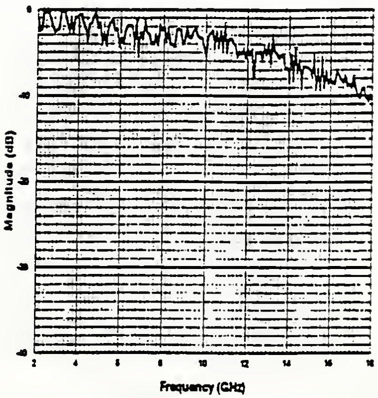

Figure 5.42 Frequency vs. Magnitude Transmission Coefficients, #8 Binder Gravel, Very Fine

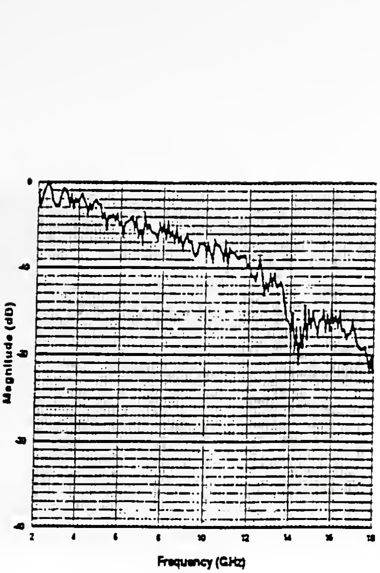

Figure 5.43 Frequency vs. Magnitude Transmission Coefficients, #8 Binder Gravel, Control

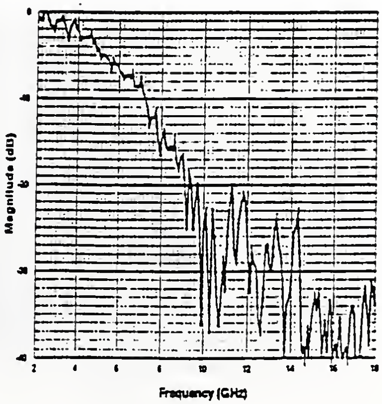

Figure 5.44 Frequency vs. Magnitude Transmission Coefficients, #8 Binder Gravel, Very Coarse

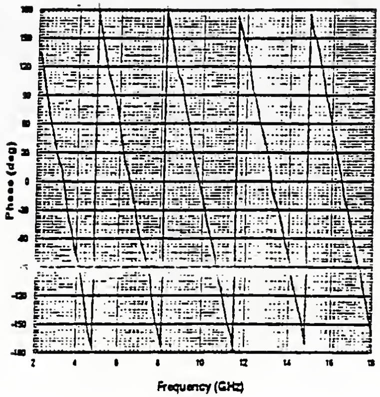

Figure 5.45 Frequency vs. Phase Transmission Coefficients, #11 Surface Gravel, Very Fine

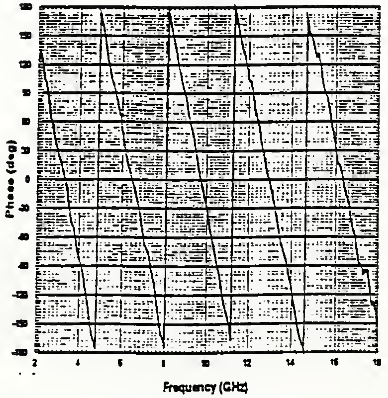

Figure 5.46 Frequency vs. Phase Transmission Coefficients, #11 Surface Gravel, Control

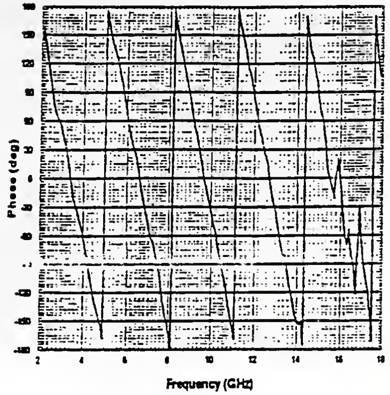

Figure 5.47 Frequency vs. Phase Transmission Coefficients, #11 Surface Gravel, Very Coarse

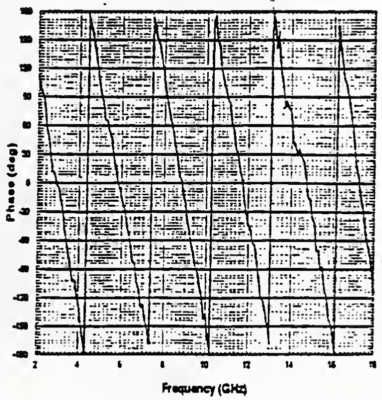

Figure 5.48 Frequency vs. Phase Transmission Coefficients, #8 Binder Gravel, Very Fine

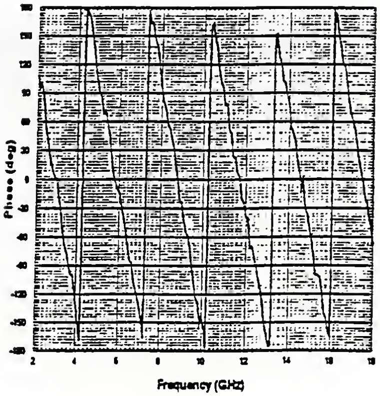

Figure 5.49 Frequency vs. Phase Transmission Coefficients, #8 Binder Gravel, Control

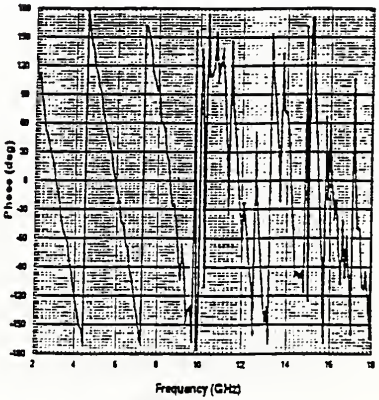

Figure 5.50 Frequency vs. Phase Transmission Coefficients, #8 Binder Gravel, Very Coarse

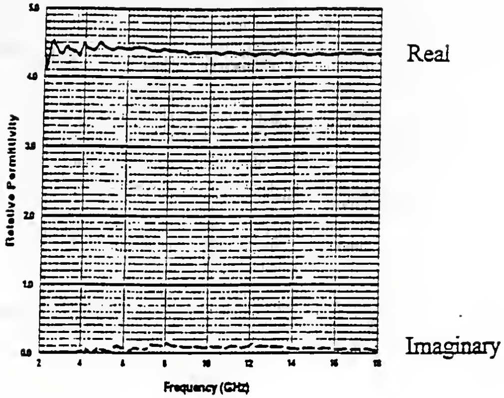

Figure 5.51 Dielectric Constant Measurement, #11 Surface Gravel, Very Fine

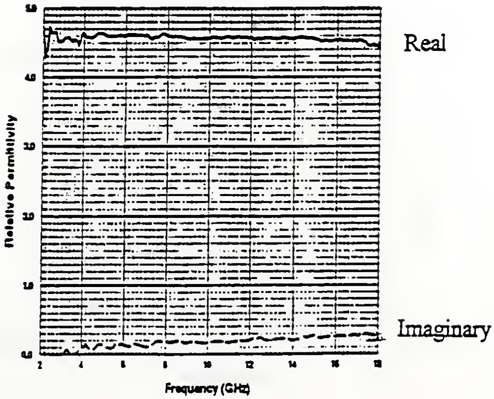

Figure 5.52 Dielectric Constant Measurement, #11 Surface Gravel, Control

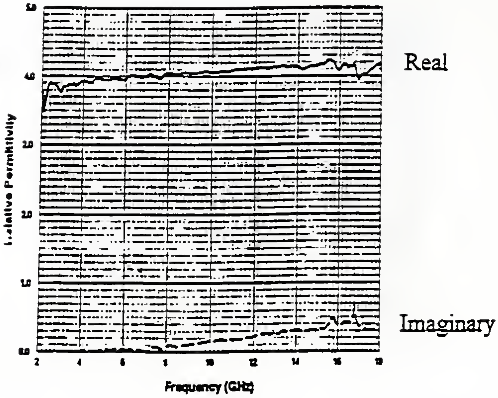

Figure 5.53 Dielectric Constant Measurement, #11 Surface Gravel, Very Coarse

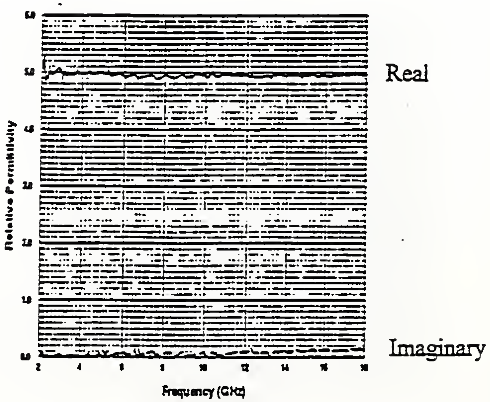

Figure 5.54 Dielectric Constant Measurement, #8 Binder Gravel, Very Fine

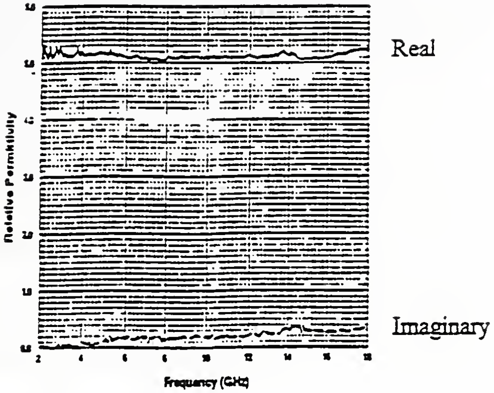

Figure 5.55 Dielectric Constant Measurement, #8 Binder Gravel, Control

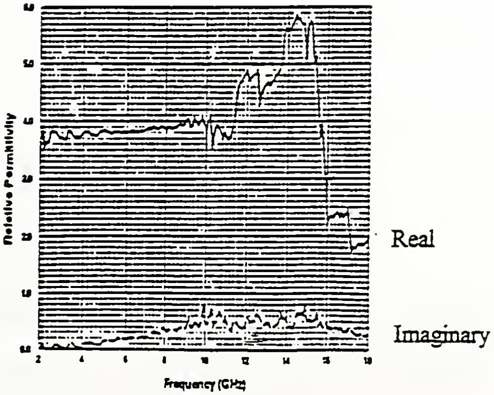

Figure 5.56 Dielectric Constant Measurement, #8 Binder Gravel, Very Coarse

CHAPTER 6. FIELD TESTS

6.1 Introduction

The previous laboratory study was conducted to determine which technologies were viable for field implementation to detect segregation. Based on these laboratory tests and preliminary field testing, the nuclear gauge appeared to be the most promising technology. Thus, an expanded field testing program was conducted using the nuclear gauge to measure in-place moisture (asphalt) content and density. Cores were taken at the same location and analyzed in the laboratory.

6.2 Field Tests

Field projects tested were identified by the Indiana Department of Transportation Operations personnel. These projects were as follows:

1. I-469 North, 0.3 and 0.7 miles after the DuPont Road exit, right lane with confinement from the left lane.

   Fort Wayne, IN.

   #8 Binder, limestone coarse aggregate and natural sand.

2. US 421 South, 1.4 and 0.8 miles from the Wabash River, right lane with confinement from the right shoulder.

   Delphi, IN.

#8 Binder, limestone coarse aggregate and natural sand.

3. I-64 East on-ramp from SR 161, full-width paving lane without confinement.

   Holland, IN.

   #9 Binder, limestone coarse aggregate and natural sand. The mix design called for 17 percent recycled asphalt pavement.

4. US 231 North, 0.6 miles north of Vincennes, right lane with confinement from the left lane.

   Vincennes, IN.

   #8 Binder, limestone coarse aggregate and natural sand.

The Fort Wayne project was used as a trial section to evaluate the testing program. At each project, two transverse sections were to be randomly located within two different sublots. The first nuclear gauge readings for a transverse section were to be taken one foot from the edge of paving lane. Subsequent readings were taken at one foot increments across the lane until there was at least two feet but not less than one foot remaining to the edge of the paving lane. In addition, by visual inspection, sites within the sublot were located and tested that appeared to be segregated, coarse and fine, and non-segregated. The Holland project was limited, consisting of only one sublot. It also started to rain at the Holland project before tests of the visually located sites were completed.

6.2.1 Preliminary Field Tests

As noted, the Fort Wayne project was used as a trial project. A problem was encountered when field nuclear density was compared with the saturated surface dry density of cores. This problem is depicted in Figures 6.1 and 6.2. The paraffin coating technique was not utilized because the asphalt was to be extracted.

On the Fort Wayne project, the nuclear gauge readings were taken the following day after paving. There was significant scatter in comparing the moisture (asphalt) content readings and extracted asphalt contents of the cores shown in Figures 6.3 and 6.4. It was surmised and confirmed through conversations with the nuclear gauge manufacturer (Brown, K., 1995), that the readings should be taken the same day, immediately after compaction. Otherwise, moisture from rain or humidity penetrating the mat's surface would affect the gauge readings. As a result, on the ensuing three projects the readings and cores were taken the same day as construction.

6.2.2 Expanded Field Tests

Field tests were conducted on the three remaining projects. At these projects, nuclear gauge readings were taken just after compaction of the pavement mat to minimize any errors in the moisture (asphalt) content readings due to humidity. Density readings were also recorded concurrently with the asphalt content readings. The field nuclear readings are summarized in Tables 6.1 through 6.3 for the additional projects. The transverse readings for density and moisture (asphalt) content are shown in Figures 6.5 through 6.9 and Figures 6.10 through 6.14, respectively.

6.3 Laboratory Analysis

To examine whether a relationship between the nuclear gauge readings and the actual pavement existed, 20.3 cm cores were taken in the exact locations where the nuclear gauge measurements were recorded. These cores were taken by the Indiana Department of Transportation Research Division and Vincennes District personnel.

The laboratory analysis was initially envisioned to involve measuring the saturated surface dry density of the cores, performing an extraction to determine the asphalt content, and performing a sieve analysis. However, results from the Fort Wayne project (Figure 6.2) indicated either the nuclear gauge or the core saturated surface dry densities were in error. As a result, on the remaining three projects a volumetric density measurement technique was employed in addition to the saturated surface dry method.

6.3.1 Density

Core density was initially measured by the saturated surface dry technique given in ASTM D-2726. Core density was also determined utilizing a technique outlined by White (1975) which assumes the cores are right cylinders. The height and diameter of a subject core is measured at three equidistant locations. The average height and the diameter of the cylinder are then used to calculate the volume of the cylinder. Subsequently, the dry weight of the core is divided by the calculated volume to determine the density.

6.3.1.1 Bulk Density Evaluation

Based on the relation of saturated surface dry (SSD) bulk density and nuclear density on the Fort Wayne project, it was hypothesized that the constant density reflected in the SSD density was a result of water that had penetrated the cores' connected air voids when the submerged weight was obtained. Subsequently, the water drained during preparation prior to obtaining the saturated surface dry weight. This would result in a lower volume and thus a higher density. The following equation outlines the calculation of bulk specific gravity (ASTM D-2726).

$$\text{Bulk Specific Gravity} = [A/(B-C)] \qquad (1)$$

where:

A = mass in grams of sample in air,

B = mass in grams of saturated surface-dry specimen in air,

C = mass in grams of sample in water.

It is obvious that a decrease in the value of B results in a lower bulk density. The bulk densities for the transverse sections are shown in Figures 6.5 through 6.9. The values for the three subsequent test locations are shown in Tables 6.1 through 6.3.

6.3.1.2 Volumetric Density

Volumetric density was calculated assuming the cores were right cylinders. Height and diameter of the cores were measured at three equidistant locations. The

average height, diameter and the dry weight were then used to calculate the cylindrical volumetric (CV) density. The CV densities for the transverse sections are shown in Figures 6.5 through 6.9. Values for the three subsequent test locations are shown in Tables 6.1 through 6.3.

6.3.1.3 Comparison of Different Densities: Random Locations

To determine the relationship between SSD and CV densities and four minute nuclear density readings, regression analysis was performed on data obtained from random locations transverse to pavement laydown. The following equation was used in the analysis to compare the densities.

$$SSD, CV = A(Nuc) + B \tag{2}$$

where:

SSD = Saturated Surface-Dried Density,

CV = Cylindrical Volumetric Density,

Nuc = Four Minute Nuclear Gauge Density Reading,

A, B = Regression Coefficients.

This analysis was performed separately on data obtained from random sublots. Two random sublots were sampled on the Delphi and Vincennes projects, and one sublot on the Holland project.

6.3.1.3.1 Delphi Project

The regression results performed on data from the two Delphi sublots are

summarize in Tables 6.4 and 6.5. Statistical analysis of sublot 1 data indicates SSD density is a poorer measure of density than CV density as evidence by the decrease in the goodness in fit between SSD and nuclear densities, 0.008, and CV and nuclear densities, 0.692, in the models. Further, the nuclear density is statistically significant in the CV model, but not in the SSD model. The same analysis of sublot 2 data indicates that neither density, SSD or CV, is statistically significant. These correlations are graphically represented in Figures 6.10 and 6.11.

6.3.1.3.2 Holland Project

The Holland project consisted of only one sublot. Analysis of this data shows that SSD density correlates well with nuclear density and CV density is not correlated with SSD density as shown by the low values in the goodness of fit of 0.332 and 0.209, respectively. This is a result of the random location within the sublot not being segregated. The lack of segregation is shown in Figure 6.24. In the SSD model, the intercept is statistically more significant than the intercept for nuclear density. This could be due to lack in true density variation, which is in part sensitive to segregation. This analysis is summarized in Table 6.6. The correlation between densities is shown in Figure 6.12.

6.3.1.3.3 Vincennes Project

Analyses of sublot 1 data shows CV density correlates better with nuclear density than SSD density when the values of goodness of fit are examined. The goodness of fit

for the SSD model is 0.559 compared to 0.941 for the CV model. In the CV model, the nuclear density is statistically more significant, F-value = 144.4, than in the SSD model, F-value = 11.43. Analysis of sublot 2 shows both models are statistically significant, with the SSD model being better than the CV model. The F-value for nuclear density in the SSD model is 80.64 compared to 28.97 in the CV model. The correlations are graphically represented in Figures 6.13 and 6.14. Tables 6.7 and 6.8 summarize the statistics for sublot 1 and sublot 2, respectively.

6.3.1.4 Comparison of Different Densities: Visual Locations

The same type of regression analysis was performed on visually identified locations as the random locations. The visually identified locations of coarsely and non-coarsely segregated areas was thought to likely have greater variations in density between the two groups. Whereas, the random locations may provide good comparisons where segregation occurred, but not as severely as the visual locations. This analysis was performed separately on the Delphi and Vincennes visually identified segregated sites.

Analysis of the Delphi data revealed that the nuclear density correlated much better with CV density than SSD density. The goodness of fit between nuclear and CV densities is 0.964 compared to 0.646 between the nuclear and SSD densities. Further, the nuclear density is statistically significant at alpha = 0.05 in the CV density model and not the SSD density model. The intercept was statistically significant at alpha = 0.05 in the SSD density model, but not in the CV model. Analysis of the Vincennes data revealed similar results. A statistical summary of the analyses is given in Tables 6.9 and 6.10 for

the Delphi and Vincennes sites, respectively. The relationship between the three densities are shown in Figures 6.15 and 6.16 for the Delphi and Vincennes sites, respectively.

6.3.2 Asphalt Content

Asphalt content of the field samples was determined by extraction of the asphalt according to ASTM D-2172, Method B. The results are shown graphically in Figures 6.17 through 6.21. Regression analysis was done for each subot comparing four minute nuclear gauge moisture (asphalt) content and extracted asphalt content. The goodness of fit for all sublots ranged from 0.11 to 0.45 showing that a strong relationship does not exist. However, when the same regression was performed for the visually located segregated locations, the goodness of fit for the Delphi and Vincennes projects are 0.59 and 0.95. This shows that visually identified locations have larger variations in asphalt content from the job mix formula and that the nuclear gauge can be used to detect these variations. The values for the three expanded test locations are shown in Tables 6.1 through 6.3.

6.3.3 Gradation

Core aggregate gradation after asphalt extraction was determined according to ASTM D-448. Based upon the job mix formulas for each project, the sieve that most nearly divided the gradation evenly was identified. This sieve was the 9.5 mm sieve for the Delphi and Vincennes projects (INDOT 25 mm nominal maximum mixture) and the

4.75 mm sieve for the Holland project (INDOT 19 mm nominal maximum mixture). The percent passing this sieve was subtracted from the actual percent passing of each core for the appropriate project. Results of the transverse locations are shown graphically in Figures 6.22 through 6.26. The values for the three expanded test locations are shown in Tables 6.1 through 6.3. Sieve analysis for the Fort Wayne project samples was not performed because of the incomplete CV density data and inappropriate field testing with the nuclear gauge as discussed previously.

6.4 Classification

The same procedure, discriminant analysis, used in Chapter five to classify the segregated laboratory samples using nuclear gauge readings was used to classify field samples. However, base pavement and mixtype variables previously included in the laboratory classification were not used in the field classification. Further, only two categories, coarse and non-coarse segregation, were used in the field classification. For this analysis, a sample was categorized as being "coarse segregation" if the gradation was more than five percent above the job mix formula on the 9.5 mm sieve, otherwise the sample was categorized as "no coarse segregation." Discriminant analysis, was used to analyze samples from the visually identified segregated and non-segregated sites. The independent variables are the nuclear gauge moisture (asphalt) content and density readings.

Initially, all of the data (transverse sections and visual sites) were classified using the nuclear density and moisture (asphalt) content. This classification was conducted

using the SAS discriminant analysis procedure (SAS Institute, 1988). Classification using all of the data created a bias towards the "none" segregated set because of there being more "none" data. Using the data for visually located segregated, coarse and fine, and non-segregated locations resulted in poor classification. This is caused by the physical properties of fine segregation. Visually identifying what appears to be fine segregation created problems because the "fine" segregation may be only a very thin layer on the surface. Whereas with the coarse segregation, the coarser aggregate does constitute a thicker layer of the segregation.

Subsequently, the data for visually identified sites was classified alone with a 100 percent success in the classification. These results are summarized in Table 6.11. Analysis was based on a plus or minus five percent passing on the 9.5 mm sieve for the Delphi and Vincennes projects. The 9.5 mm sieve was selected because for both job mix formulas, this sieve evenly divided the mix as 50/50 retained/passing. As previously mentioned, the visual data set for Holland was incomplete due to rain. The results of the discriminant analysis are in Appendix E. Figure 6.27 was prepared from the discriminant analysis of the visual data. The lines of posterior probability shown in Figure 6.26 apply to coarsely identified locations only.

Table 6.1 Characterization of Delphi Field Samples and Field Tests

Sample	Bulk Specific Gravity	Cylindrical Volumetric Specific Gravity	Extracted Asp. Content, percent	Nuclear* Specific Gravity	Nuclear Asp. Content, percent	Diff. in Grad. on 9.5 mm Sieve from JMF, percent
1A	2.27	2.03	4.65	2.18	4.2	-3.64
1B	2.26	2.09	4.54	2.18	4.7	-1.69
1C	2.27	2.16	5.14	2.28	4.8	-5.23
1D	2.24	2.23	4.80	2.51	4.6	7.33
1E	2.28	2.22	4.86	2.36	5.3	0.14
1F	2.27	2.21	4.63	2.34	5.2	5.81
1G	2.25	2.18	5.14	2.28	5.6	6.17
1H	2.21	2.21	5.34	2.32	5.4	11.15
1I	2.27	2.20	4.79	2.42	4.9	1.78
1J	2.26	2.09	5.50	2.25	4.7	-7.03
1K	2.31	2.09	4.97	2.27	4.1	-22.75
1L	2.22	2.08	4.08	2.22	4.3	-14.78
8A	2.27	2.06	4.27	2.05	4.9	-10.03
8B	2.26	2.13	5.18	2.00	4.9	-0.17
8C	2.28	2.15	5.29	2.10	5.3	1.00
8D	2.24	2.16	6.05	2.16	5.5	9.34
8E	2.26	2.13	4.98	2.16	5.4	1.04
8F	2.24	2.14	5.08	2.27	5.4	8.73
8G	2.26	2.11	4.94	2.31	5.1	-0.91
8H	2.25	2.17	4.85	2.33	5.2	9.78
8I	2.27	2.11	4.78	2.35	5.3	-2.57
8J	2.26	2.06	4.83	2.29	4.9	1.79
8K	2.29	2.05	4.41	2.26	4.8	-3.28
8L	2.28	2.17	4.83	2.17	4.8	-4.88
2	2.28	2.19	4.40	2.00	5.1	-6.71
3	2.27	2.02	5.28	2.20	5.4	0.24
4	2.26	2.22	6.21	2.16	5.5	14.56
5	2.29	2.00	4.14	1.99	4.7	-9.74
6	2.28	2.07	4.68	2.21	5.5	1.84
7	2.30	2.03	4.21	1.96	4.8	-16.99

* Converted from English units (pcf) to unit weight.

Table 6.2 Characterization of Holland Field Samples and Field Tests

Sample	Bulk Specific Gravity	Cylindrical Volumetric Specific Gravity	Extracted Asp. Content, percent	Nuclear* Specific Gravity	Nuclear Asp. Content, percent	Diff. in Grad. on 9.5 mm Sieve from JMF, percent
A	2.21	2.04	5.17	2.18	5.5	4.44
B	2.23	2.08	4.31	2.22	5.3	1.32
C	2.23	2.09	5.26	2.27	5.4	-1.92
D	2.21	2.09	5.96	2.20	5.5	4.03
E	2.23	2.16	6.11	2.29	5.8	3.22
F	2.20	2.16	5.56	2.21	6.2	5.57
G	2.21	2.12	5.54	2.28	5.6	2.71
H	2.22	2.10	4.91	2.26	5.6	0.36
I	2.22	2.08	4.89	2.21	5.7	1.42
J	2.21	2.00	4.87	2.22	5.6	-1.67
K	2.24	2.02	5.30	2.27	5.5	-1.70
L	2.19	1.99	4.89	2.16	5.8	0.76
M	2.23	1.97	4.61	2.26	5.7	-2.37
N	2.23	1.96	4.91	2.17	5.2	-2.54
2	2.21	2.00	4.85	2.08	5.3	-2.48

* Converted from English units (pcf) to unit weight.

Table 6.3 Characterization of Vincennes Field Samples and Field Tests

Sample	Bulk Specific Gravity	Cylindrical Volumetric Specific Gravity	Extracted Asp. Content, percent	Nuclear* Specific Gravity	Nuclear Asp. Content, percent	Diff. in Grad. on 9.5 mm Sieve from JMF, percent
1A	2.32	2.11	3.39	2.16	3.2	-8.79
1B	2.34	2.26	3.79	2.30	3.5	-0.76
1C	2.37	2.31	4.15	2.38	3.6	3.48
1D	2.38	2.33	4.37	2.39	3.8	8.80
1E	2.36	2.30	3.74	2.35	3.6	-1.36
1F	2.36	2.18	4.09	2.25	3.4	-10.59
1G	2.34	2.27	3.83	2.31	3.7	3.06
1H	2.33	2.25	4.26	2.30	3.6	1.61
1I	2.34	2.23	3.81	2.31	3.5	-3.97
1J	2.32	2.21	3.80	2.28	3.8	3.07
1K	2.33	2.03	3.43	2.14	3.1	-10.35
5A	2.31	2.29	4.38	2.23	4.1	1.03
5B	2.35	2.30	4.46	2.33	4.0	3.97
5C	2.39	2.35	5.14	2.38	4.2	4.91
5D	2.39	2.34	5.21	2.38	4.3	5.15
5E	2.38	2.34	5.06	2.40	4.1	6.08
5F	2.36	2.30	4.51	2.33	3.7	-4.84
5G	2.38	2.33	5.01	2.36	3.9	5.28
5H	2.37	2.32	4.93	2.36	3.9	3.97
5I	2.33	2.28	4.93	2.33	3.6	7.19
5J	2.31	2.18	4.08	2.24	3.4	-6.82
5K	2.27	2.14	4.39	2.22	3.6	1.14
2	2.35	2.24	3.71	2.23	3.4	-2.98
3	2.33	2.03	2.98	2.09	3.0	-13.34
4	2.36	2.32	4.10	2.41	3.7	1.34
6	2.36	2.18	4.10	2.27	3.9	1.94
7	2.35	2.27	4.38	2.37	3.9	-3.72
8	2.38	2.31	4.31	2.34	4.0	0.46

* Converted from English units (pcf) to unit weight.

Table 6.4 Statistical Summary of Delphi Sublot #1, Transverse Density Data

Model	F-Value, α-Value for Model	R^2	Estimate for Nuc	t-Value, α-Value for Nuc	Estimate for Intercept	t-Value, Pr> t for Intercept (B)
SSD = A(Nuc) + B	0.08, 0.784	0.008	-0.025	-0.28, 0.7835	144.68	11.21, 0.0001
CV = A(Nuc) + B	22.49, 0.0008	0.692	0.596	4.74, 0.0008	48.50	2.69, 0.0229

Table 6.5 Statistical Summary of Delphi Sublot #2, Transverse Density Data

Model	F-Value, α-Value for Model	R^2	Estimate for Nuc	t-Value, α-Value for Nuc	Estimate for Intercept	t-Value, Pr> t for Intercept (B)
SSD = A(Nuc) + B	0.15, 0.702	0.015	-0.017	-0.39, 0.702	143.50	23.98, 0.0001
CV = A(Nuc) + B	0.04, 0.8532	0.004	-0.023	-0.19, 0.8532	135.53	8.19, 0.0001

Table 6.6 Statistical Summary of Holland, Transverse Density Data

Model	F-Value, α-Value for Model	R^2	Estimate for Nuc	t-Value, α-Value for Nuc	Estimate for Intercept	t-Value, Pr> t for Intercept (B)
SSD = A(Nuc) + B	5.97, 0.031	0.332	0.164	2.44, 0.031	115.68	12.40, 0.0001
CV = A(Nuc) + B	3.18, 0.1001	0.209	0.693	1.78, 0.1001	32.21	0.59, 0.5629

Table 6.7 Statistical Summary of Vincennes Sublot #1, Transverse Density Data

Model	F-Value, α-Value for Model	R^2	Estimate for Nuc	t-Value, α-Value for Nuc	Estimate for Intercept	t-Value, Pr> t for Intercept (B)
SSD = A(Nuc) + B	11.43, 0.0081	0.559	0.203	3.38, 0.0081	117.24	13.64, 0.0001
CV = A(Nuc) + B	144.40, 0.0001	0.941	1.089	12.02, 0.0001	-16.65	-1.29, 0.2306

Table 6.8 Statistical Summary of Vincennes Sublot #2, Transverse Density Data

Model	F-Value, α-Value for Model	R^2	Estimate for Nuc	t-Value, α-Value for Nuc	Estimate for Intercept	t-Value, Pr> t for Intercept (B)
SSD = A(Nuc) + B	80.64, 0.0001	0.900	0.586	8.98, 0.0001	61.60	6.51, 0.0001
CV = A(Nuc) + B	28.97, 0.0004	0.763	0.937	5.38, 0.0004	6.93	0.27, 0.7900

Table 6.9 Statistical Summary of Delphi Visually Identified Segregation Density Data

Model	F-Value, α-Value for Model	R^2	Estimate for Nuc	t-Value, α-Value for Nuc	Estimate for Intercept	t-Value, Pr> t for Intercept (B)
SSD = A(Nuc) + B	7.31, 0.054	0.646	-0.098	-2.70, 0.0539	155.12	32.85, 0.0001
CV = A(Nuc) + B	107.57, 0.0005	0.964	0.831	10.37, 0.0005	23.38	2.24, 0.0889

Table 6.10 Statistical Summary of Vincennes Visually Identified Segregation Density Data

Model	F-Value, α-Value for Model	R^2	Estimate for Nuc	t-Value, α-Value for Nuc	Estimate for Intercept	t-Value, Pr> t for Intercept (B)
SSD = A(Nuc) + B	3.75, 0.125	0.484	0.083	1.94, 0.125	135.07	22.05, 0.0001
CV = A(Nuc) + B	20.50, 0.0106	0.837	0.864	4.53, 0.0106	15.64	0.57, 0.5967

Table 6.11 Discriminant Analysis: Visual Segregation Classification

From Segregation		Coarse	None	Total
Coarse	Number of Observations Percent	4 100	0 0	4 100
None	Number of Observations Percent	0 0	8 100	8 100
Total	Number of Observations Percent	4 33.33	8 66.67	12 100

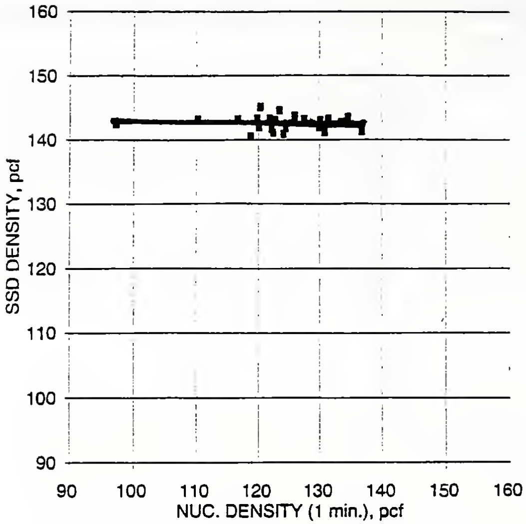

Figure 6.1 Ft. Wayne, All Density Data, 1 Minute Reading

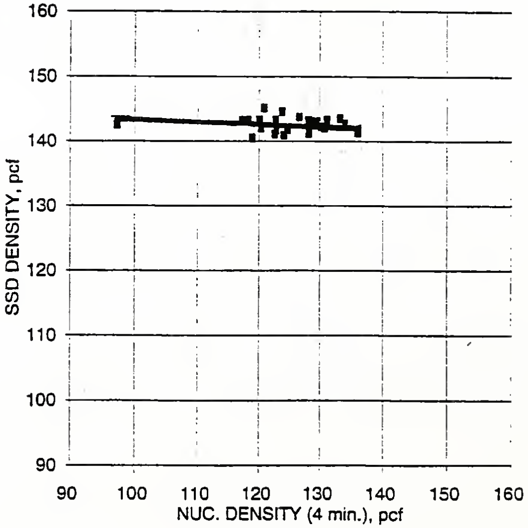

Figure 6.2 Ft. Wayne, All Density Data, 4 Minute Reading

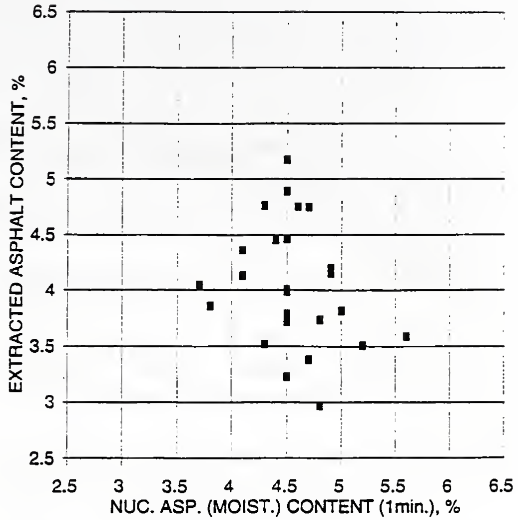

Figure 6.3 Ft. Wayne, All Moisture (Asphalt) Content Data, 1 Minute Reading

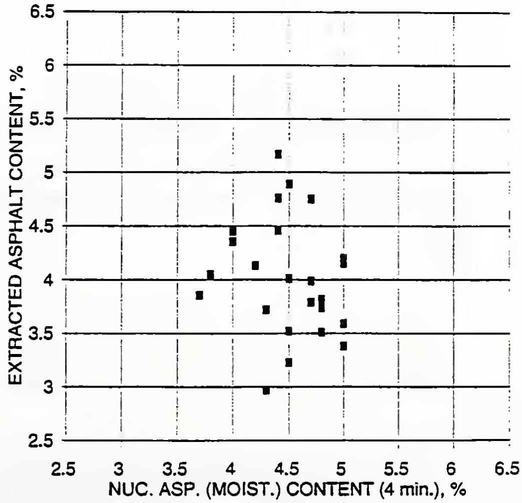

Figure 6.4 Ft. Wayne, All Moisture (Asphalt) Content Data, 4 Minute Reading

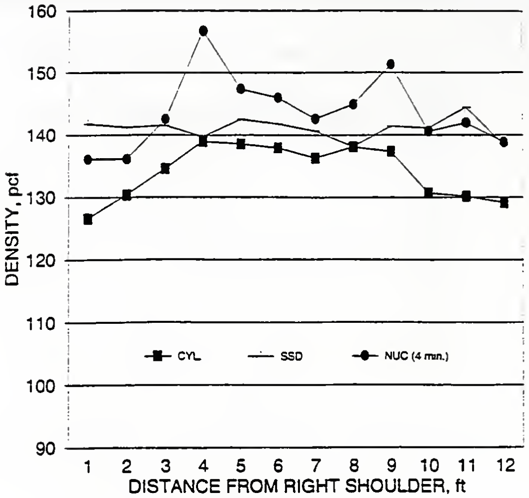

Figure 6.5 Delphi, Sublot #1, Density, 4 Minute Reading

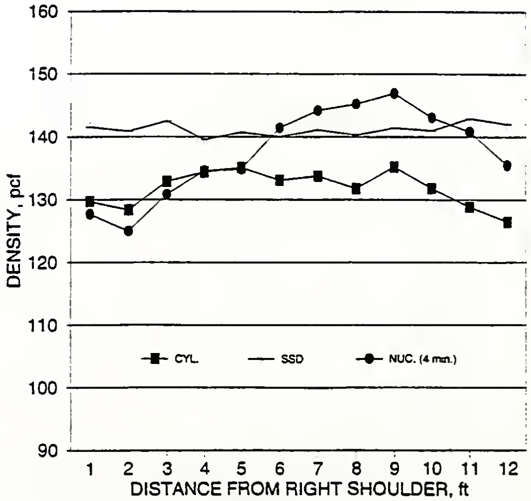

Figure 6.6 Delphi, Sublot #2, Density, 4 Minute Reading

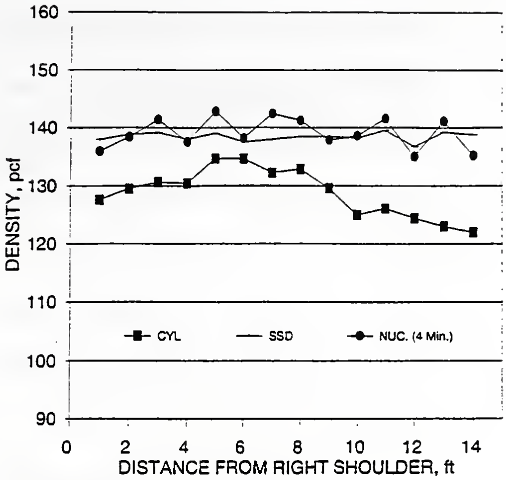

Figure 6.7 Holland, Density, 4 Minute Reading

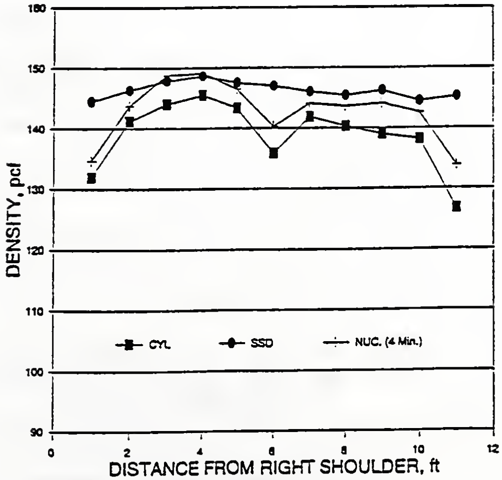

Figure 6.8 Vincennes, Sublot #1, Density, 4 Minute Reading

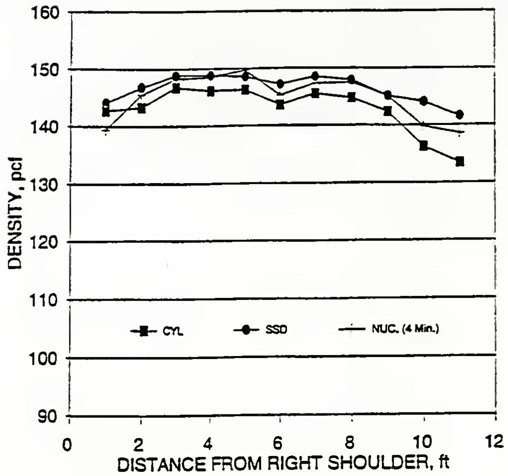

Figure 6.9 Vincennes, Sublot #2, Density, 4 Minute Reading

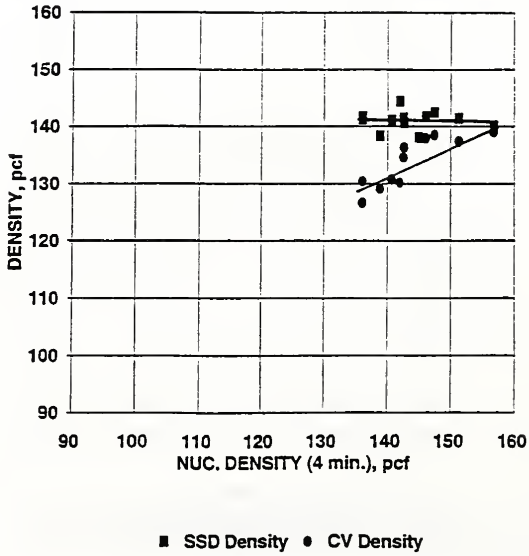

Figure 6.10 Delphi, Sublot #1, Random Location, Density Comparisons

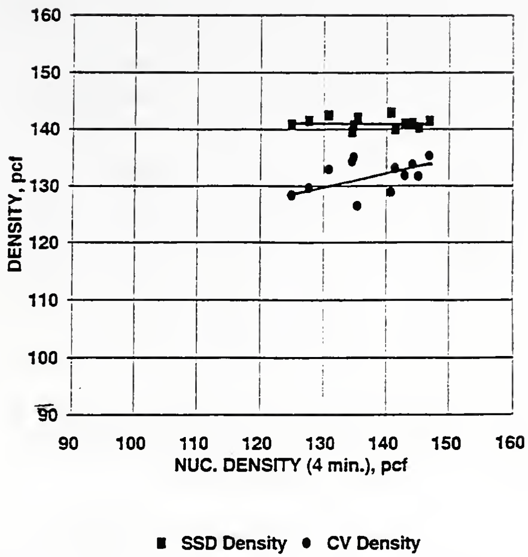

Figure 6.11 Delphi, Sublot #2, Random Location, Density Comparisons

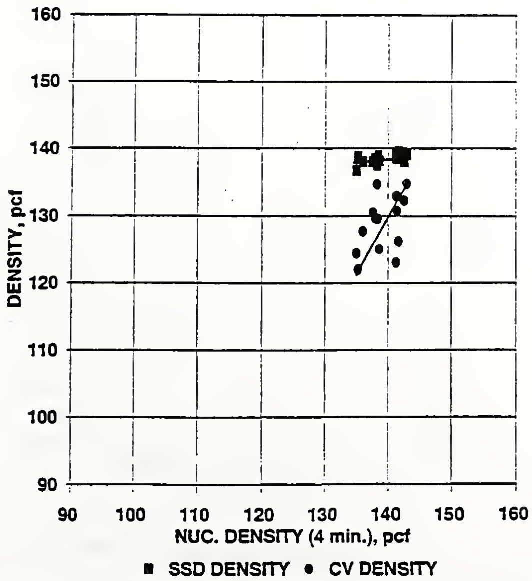

Figure 6.12 Holland, Random Location, Density Comparisons

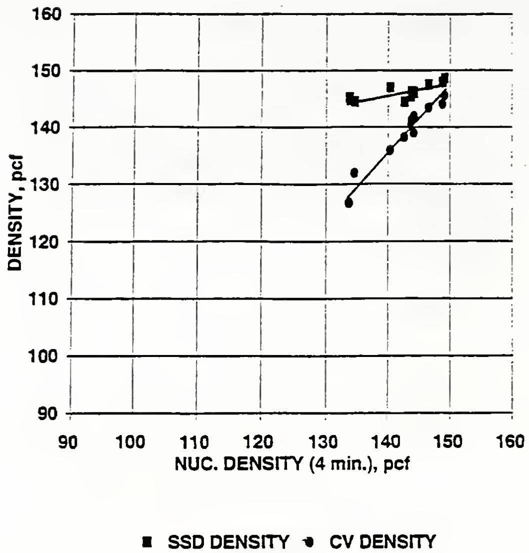

Figure 6.13 Vincennes, Sublot #1, Random Location, Density Comparisons

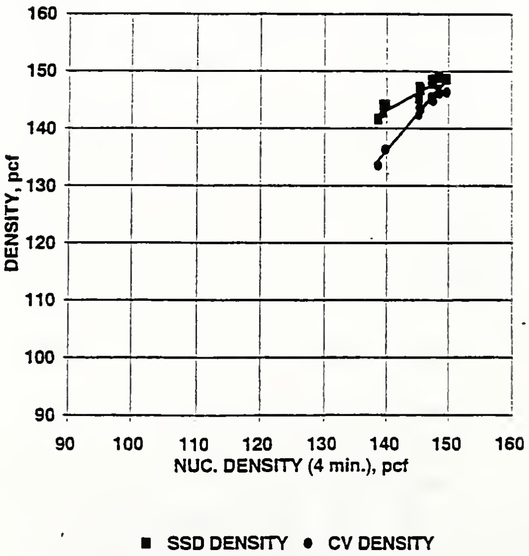

Figure 6.14 Vincennes, Sublot #2, Random Location, Density Comparisons

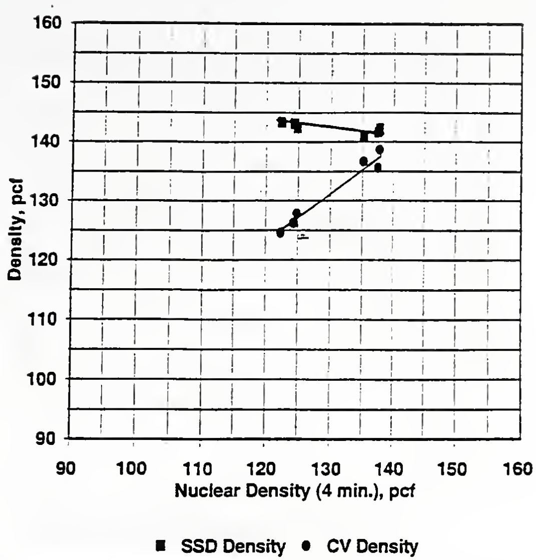

Figure 6.15 Delphi, Visual Locations, Density Comparisons

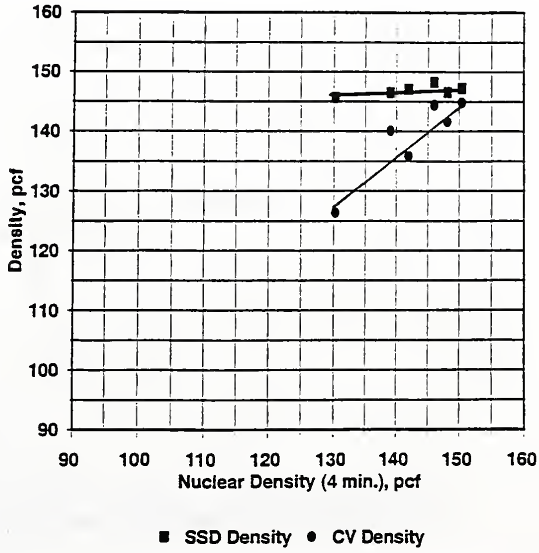

Figure 6.16 Vincennes, Visual Locations, Density Comparisons

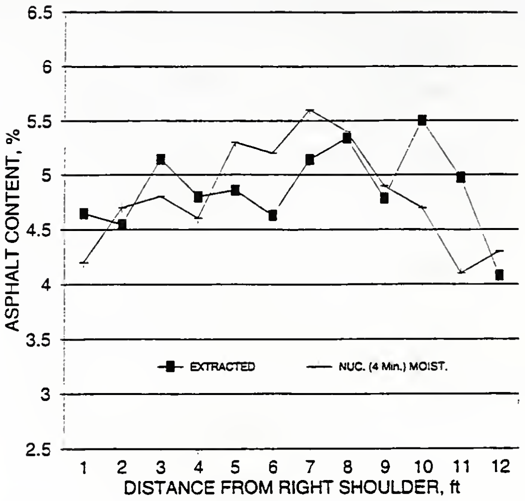

Figure 6.17 Delphi, Sublot #1, Moisture (Asphalt) Content, 4 Minute Reading

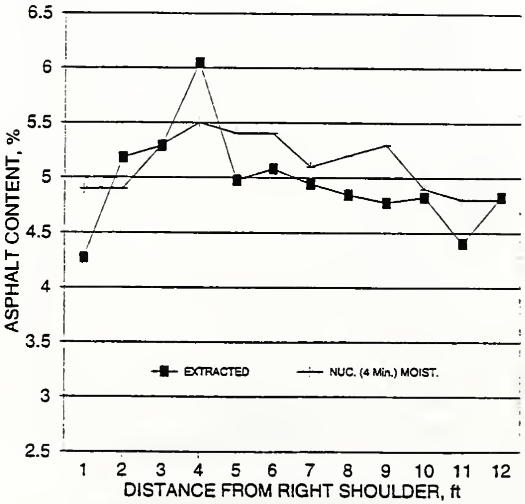

Figure 6.18 Delphi, Sublot #2 Moisture (Asphalt) Content, 4 Minute Reading

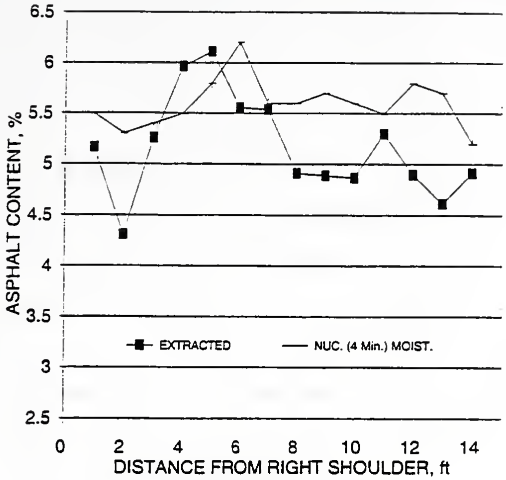

Figure 6.19 Holland, Moisture (Asphalt) Content, 4 Minute Reading

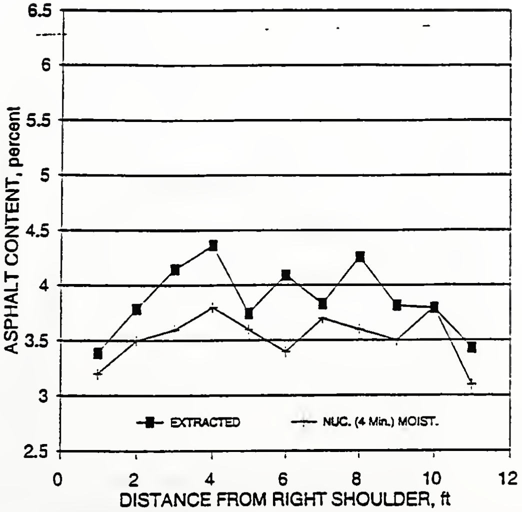

Figure 6.20 Vincennes, Sublot #1, Moisture (Asphalt) Content, 4 Minute Reading

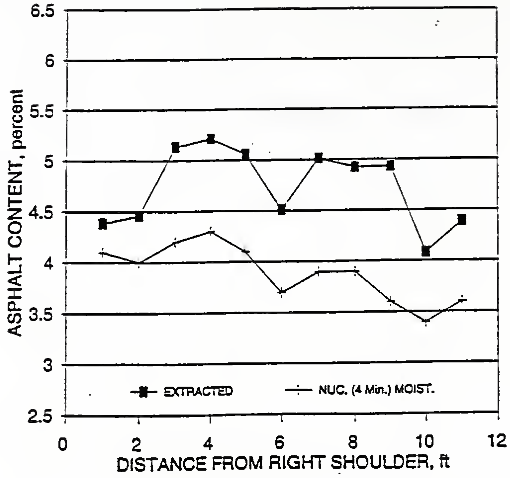

Figure 6.21 Vincennes, Sublot #2, Moisture (Asphalt) Content, 4 Minute Reading

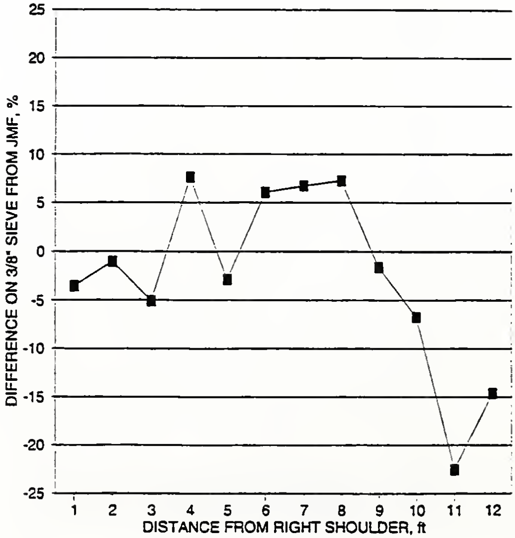

Figure 6.22 Delphi, Sublot #1, Difference in Gradation on the 9.5 mm Sieve

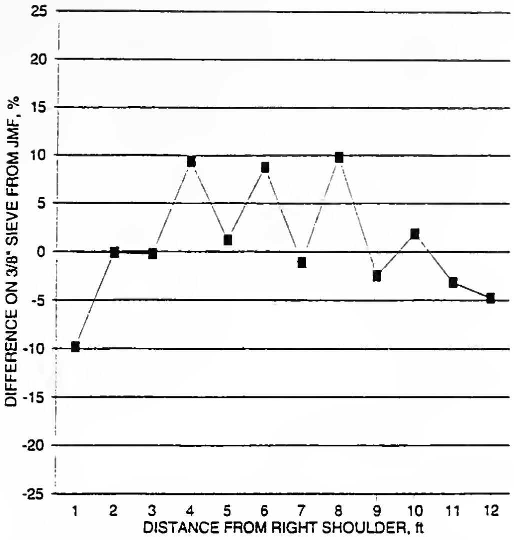

Figure 6.23 Delphi, Sublot #2, Difference in Gradation on the 9.5 mm Sieve

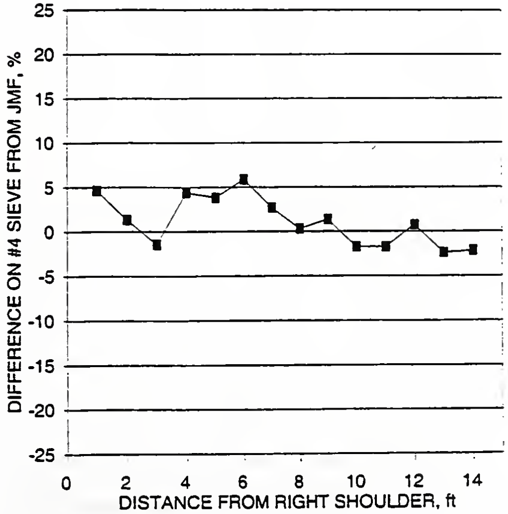

Figure 6.24 Holland, Difference in Gradation on the 4.75 mm Sieve

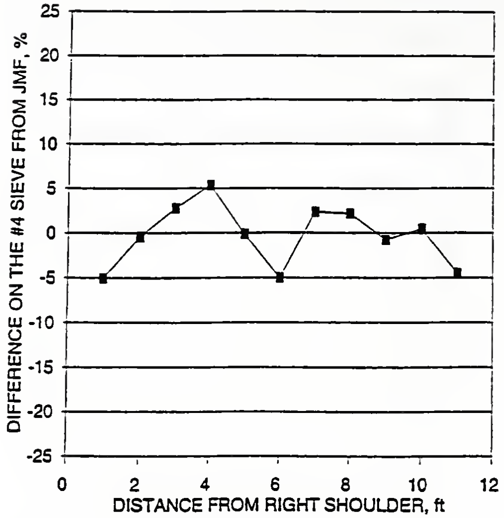

Figure 6.25 Vincennes, Sublot #1, Difference in Gradation on the 9.5 mm Sieve

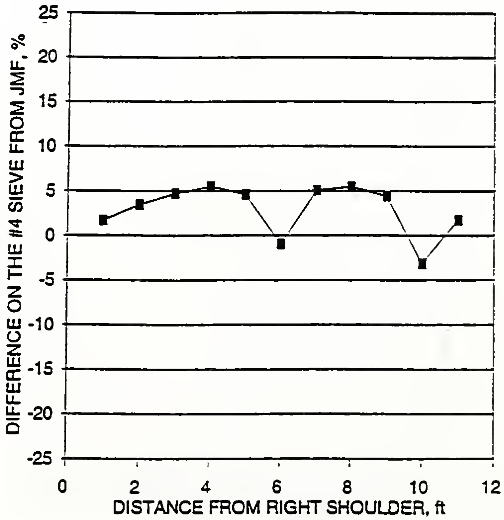

Figure 6.26 Vincennes, Sublot #2, Difference in Gradation on the 9.5 mm Sieve

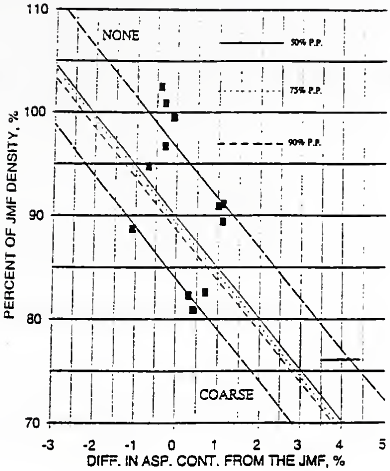

Figure 6.27 Coarse Segregation Classification Probability (#8 Binder, Greater than -5% Difference on the 9.5 mm Sieve)

CHAPTER 7. FLEXURAL FATIGUE TESTING OF SEGREGATED MIXTURES

7.1 Introduction

Flexural fatigue testing was performed to examine the difference in fatigue of mixtures with varying levels of segregation. In the study, surface and binder gravel mixtures were tested at the five levels of segregation. The following describes procurement and preparation of samples, test apparatus, testing procedures, results and analysis.

7.2 Preparation of Samples for Fatigue Testing

Samples were prepared in a multi-step process. This process included:

1. Drying aggregate to a constant weight,
2. Sieving aggregate into stockpiles by size,
3. Recombining aggregate to satisfy required gradation,
4. Heating combined aggregate and asphalt to predetermined mixing temperature based on the asphalt viscosity,
5. Mixing aggregate and asphalt,
6. Curing mix for approximately one hour,
7. Preheating Purdue Linear Compactor (PLC) mold to compaction temperature using an infrared heater shown in Figure 7.1,

8. Compacting slabs in the PLC (slab dimensions of 102 mm high by 550 mm long and 305 mm wide) to their predetermined laboratory density as discussed in Chapter 4,
9. Saw three beams measuring approximately 380 mm long by 75 mm wide by 75 mm high using a water-cooled diamond saw blade (Figure 7.2). Figures 7.3 and 7.4 show the beams' layout on a schematic of the slabs,
10. Drying beams to a constant weight at room temperature.

    Once the beams reached a constant weight, the final weight and dimensions were determined and recorded. These measurements allow the density and cross-sectional area of each specimen to be calculated. The cross-sectional area is used in the strain calculation for the flexural fatigue test.
11. Bonding an indented aluminum button to the center of each beam with epoxy. The probe of the linear variable differential transducer (LVDT) is placed in the indenture of the button to minimize movement. The LVDT measures beam vertical displacement.
12. Placement of beams in an environmental chamber for 3 hours to allow the specimens to reach 25 degrees Celsius prior to testing.

There was some difficulty in producing quality beams for the binder, very coarse level of segregation. The saw blade raveled the poorly bonded coarse aggregate from the mixture.

7.3 Test Apparatus

A Materials Testing Systems Corporation (MTS) electro-hydraulic testing machine was used for applying loads to the beam specimens. The beams were held in a load frame built for repeated flexural tests and was contained within an environmental chamber capable of maintaining a constant temperature within 0.5 degrees Celsius.

A Shaevitz type GCD-120-050 linear variable differential transducer (LVDT) was used to measure the deflection of a subject beam during testing. The tip of the LVDT was placed in the indenture of the aluminum button that was previously bonded to the center of the test beam. The MTS system and repeated flexure frame in the environmental chamber are shown in Figures 7.5 and 7.6, respectively. LABTECH NOTEBOOK software (Labtech Notebook, 1991) was used to record data automatically using a 12 bit DT2801-A A/D conversion board mounted in a personal computer. The strain level was manually controlled by monitoring the voltage level of the LVDT using an oscilloscope.

7.4 Test Procedures

Prior to installation of a beam in the flexural test apparatus, the loading clamps were adjusted vertically to the same level as the support/reaction clamps. The centers of the two support/load clamps are 50 mm from the beam center and 100 mm from the centers of two reaction clamps. Two layers of teflon were placed between a subject beam and the clamps to reduce friction which could cause shearing stresses near the clamps creating moment in the test portion of a specimen.

All beams were tested in a controlled strain mode at 25 degrees Celsius using a one hertz haversine wave with a 0.1 second loading period and a 0.9 second rest period. A specimen is tested at a predetermined constant deflection. This deflection is used to calculate the extreme fiber strain using the following equation.

$$\text{Strain, in/in} = (12H \times D)/(3L^2-4A^2) \quad (1)$$

where:

H = Specimen height, inches

D = Deflection of the beam at the center, inches

L = Reaction span length, inches

A = Distance between support and first applied load, inches

As a specimen fatigues, it requires a lower load to attain the desired deflection (i.e. this stiffness decreases). Beams were tested until the flexural stiffness modulus was 50 percent of the initial stiffness modulus measured at the 200th load application. Data acquisition was performed automatically by a personal computer with the Labtech Notebook software interacting with an MTS control board.

7.5 Fatigue Test Results

The fatigue results for the surface gravel mixture are shown in and Tables 7.1 through 7.5. Results for the gravel binder mixture are shown in Tables 7.6 through 7.10. All of the results for the two mix sizes and different levels of segregation exhibit the typical trend associated with decreasing strain: an increase in the number of cycles to failure (Yoder and Witzak, 1975).

7.6 Analysis

Two types of statistical analysis of the fatigue test results were performed. In the first, a regression analysis of data for each level of segregation was conducted separately.

Predictive equations for each level of segregation for both gravel mixes were developed. The predictive equations were of the form shown in Equation 1 because the analysis was performed on translated data. The data was translated by taking the logarithm to the base 10 of both the strain and number of cycles to failure.

$$Log_{10}(N_f) = A + B \times Log_{10}(\varepsilon) \tag{2}$$

where:

N_f = Number of cycles to failure,

ε = Strain, in/in, and

A, B = Regression Constants.

This equation is then presented in its classical form in equation 3 (Yoder and Witzak, 1975).

$$N_f = k(1/\varepsilon)^C \tag{3}$$

where:

k, C = values based on regression constants.

However, the analysis presented here is based on the following equation.

$$N_f = D(\varepsilon)^B \tag{4}$$

where:

D = 10^A,

A, B = Regression constants defined in equation 2.

The F-values for the models and regression variables are shown in Table 7.11. The values of B and D for the models, as expressed in equation 2, are listed in Table 7.12. The predicted fatigue equations for the gravel surface and binder mixtures with the five levels of segregation are shown in Figures 7.7 and 7.8, respectively.

In the second analysis, a regression was performed by mix size with all five levels of segregation. The logarithm of strain to the base 10, level of segregation and the interaction between the two variables were included in the model. Level of segregation was used as a class variable. The purpose of this analysis was to examine the levels of segregation and test whether the performance of the different levels of segregation was statistically different. The form of this model for both the surface and binder mixtures was as follows.

$$Log_{10}(Nf) = A + B\times Log_{10}(\varepsilon) + D\times LOS + E\times Log_{10}(\varepsilon)\times LOS \qquad (5)$$

where:

LOS = Level of Segregation (1, 2, 3, 4, 5),

D, E = Regression Constants.

Table 7.13 summarizes the model statistics for the surface gravel and binder gravel

mixtures. Overall, the models were statistically significant for the logarithm of strain to the base 10 at the 99 percent level. The level of segregation was significant for the surface and binder mixes at the 94 and 90 percent levels, respectively. Statistically, the interaction term was significant at the 90 and 87 percent levels for the surface and binder mixes, respectively. This poor significance level of the interaction term implies that models of the logarithm to the base 10 of number of cycles to failure and strain are parallel functions dependent on the level of segregation.

7.7 Performance Comparison of Different Levels of Segregation

Compared with the control mixture (no segregation) fatigue performance of both the gravel surface and binder mixtures is reduced with coarser levels of segregation. Finer levels of segregation for the gravel binder mixture exhibited improved fatigue performance. The fine level of segregation for the gravel surface mixture performed poorer than the control mixture, while the very fine level performed better performance than the control mixture. The relative performance of the mixtures are shown in Figures 7.7 and 7.8.

The predictive equations, outlined in Table 7.12, can be used to estimate the number of cycles to failure at a given strain level. Examination of Figures 7.7 and 7.8 show that all five levels of segregation for both the gravel surface and binder mixtures were tested above and below the 0.0007 in/in strain level. Comparison of the mixtures tested at the 0.0007 in/in strain level and relative performance to the control mixture are summarized in Table 7.14.

For the gravel surface mixture at the 0.0007 in/in strain level, the coarse, and very coarse levels of segregation models predict the number of cycles to failure would lead to a reduction in fatigue performance of 24.1 and 81.6 percent compared to the control level, respectively. However, the gravel surface mixture's fine and very fine level of segregation model predicts a decrease of 13.9 and an increase of 75.3 percent in the number of cycles to failure compared to the control level of segregation, respectively.

For the gravel binder mixture at the 0.0007 in/in strain level, the coarse and very coarse levels of segregation, a predicted number of cycles to failure would lead to 49.9 and 16.8 percent reduction in fatigue life compared to the control level of segregation. The same comparison for the very fine and fine levels of segregation for the gravel binder mixture, leads to an estimated 512.8 and 190.3 percent increase in fatigue performance compared to the control level of segregation.

Table 7.1 Surface Gravel, Very Fine Segregation Fatigue Test Results

Sample	Strain, in/in	Cycles to Failure
1	0.000417	60373
2	0.000959	26529
3	0.000820	16200
4	0.000841	11236
5	0.001088	9246
6	0.001258	3506
7	0.001326	1348

Table 7.2 Surface Gravel, Fine Segregation Fatigue Test Results

Sample	Strain, in/in	Cycles to Failure
1	0.000469	47690
2	0.000716	24836
3	0.000598	18297
4	0.000732	8971
5	0.000684	4715
6	0.000831	4234
7	0.000954	1644

Table 7.3 Surface Gravel, Control Segregation Fatigue Test Results

Sample	Strain, in/in	Cycles to Failure
1	0.000416	99280
2	0.000274	52248
3	0.000620	34507
4	0.000741	13033
5	0.000892	6229
6	0.000791	4068
7	0.001166	2981

Table 7.4 Surface Gravel, Coarse Segregation Fatigue Test Results

Sample	Strain, in/in	Cycles to Failure
1	0.000449	49100
2	0.000546	26107
3	0.000630	15923
4	0.000587	15217
5	0.000757	7351
6	0.000839	3217
7	0.000927	3867

Table 7.5 Surface Gravel, Very Coarse Segregation Fatigue Test Results

Sample	Strain, in/in	Cycles to Failure
1	0.000384	32486
2	0.000435	25355
3	0.000469	8364
4	0.000610	3851
5	0.000644	3260
6	0.000898	737
7	0.000944	649

Table 7.6 Binder Gravel, Very Fine Segregation Fatigue Test Results

Sample	Strain, in/in	Cycles to Failure
1	0.000595	36696
2	0.000580	22312
3	0.000820	19487
4	0.000974	12491
5	0.001055	10561
6	0.001178	5818
7	0.001408	2876

Table 7.7 Binder Gravel, Fine Segregation Fatigue Test Results

Sample	Strain, in/in	Cycles to Failure
1	0.000453	73744
2	0.000528	21482
3	0.000611	13247
4	0.000698	10139
5	0.000820	5891
6	0.001012	2899
7	0.001173	1874

Table 7.8 Binder Gravel, Control Segregation Fatigue Test Results

Sample	Strain, in/in	Cycles to Failure
1	0.000376	48950
2	0.000369	22741
3	0.000471	11615
4	0.000555	3715
5	0.000717	3216
6	0.000617	3073
7	0.001000	2375

Table 7.9 Binder Gravel, Coarse Segregation Fatigue Test Results

Sample	Strain, in/in	Cycles to Failure
1	0.000238	37113
2	0.000318	23767
3	0.000386	10025
4	0.000449	5760
5	0.000595	3320
6	0.000696	1545
7	0.000759	1524

Table 7.10 Binder Gravel, Very Coarse Segregation Fatigue Test Results

Sample	Strain, in/in	Cycles to Failure
1	0.000237	52200
2	0.000285	40563
3	0.000402	13967
4	0.000462	8179
5	0.000463	7164
6	0.000602	5144
7	0.000649	3851

Table 7.11 Statistical Values for Individual Level of Segregation Regression Models

Mixture	Level of Segregation	Model, F-Value (Pr > F)	Intercept A. Pr > |T|	$Log_{10}(\varepsilon)$. Pr > |T|
Surface Gravel	Very Fine	13.69 (0.0140)	0.1103	0.0140
	Fine	15.88 (0.0105)	0.0355	0.0105
	Control	15.67 (0.0108)	0.1326	0.0108
	Coarse	121.55 (0.0001)	0.0007	0.0001
	Very Coarse	221.13 (0.0001)	0.0001	0.0001
Binder Gravel	Very Fine	37.71 (0.0017)	0.0415	0.0017
	Fine	138.82 (0.0001)	0.0006	0.0001
	Control	19.57 (0.0069)	0.0471	0.0069
	Coarse	288.65 (0.0001)	0.0001	0.0001
	Very Coarse	226.23 (0.0001)	0.0001	0.0001

Table 7.12 Values of Regression Constants B and C for N_f Prediction Models

Mixture	Level of Segregation	B	D
Surface Gravel	Very Fine	-2.77583	3.70×10^{-5}
	Fine	-4.45555	8.06×10^{-11}
	Control	-2.39651	3.32×10^{-4}
	Coarse	-3.82594	7.79×10^{-9}
	Very Coarse	-4.37920	3.40×10^{-11}
Binder Gravel	Very Fine	-2.40919	5.51×10^{-4}
	Fine	-3.54702	6.71×10^{-8}
	Control	-2.91536	2.34×10^{-6}
	Coarse	-2.93198	1.01×10^{-6}
	Very Coarse	-2.70017	9.04×10^{-6}

Table 7.13 Statistical Values for Level of Segregation Regression Models

Mixture	Full Model, F-value (Pr > F)	$Log_{10}(\varepsilon)$, F-value (Pr > F)	LOS, F-value (Pr > F)	$Log_{10}(\varepsilon)$*LOS, F-value (Pr > F)
Surface Gravel	16.91 (0.0001)	115.89 (0.0001)	2.63 (0.0585)	2.24 (0.0933)
Binder Gravel	36.08 (0.0001)	291.46 (0.0001)	1.33 (0.1143)	1.08 (0.0932)

Table 7.14 Effect of Level of Segregation on Fatigue Performance

Mixture	Level of Segregation	Strain, in/in	Predicted Cycles to Failure	Performance Relative to the Control Level of Segregation, Percent
Gravel Surface	Very Fine	0.0007	21168	75.3
	Fine	0.0007	9187	-13.9
	Control	0.0007	12075	N/A
	Coarse	0.0007	9162	-24.1
	Very Coarse	0.0007	2226	-81.6
Gravel Binder	Very Fine	0.0007	21974	512.8
	Fine	0.0007	10404	190.2
	Control	0.0007	3586	N/A
	Coarse	0.0007	1796	-49.9
	Very Coarse	0.0007	2985	-16.8

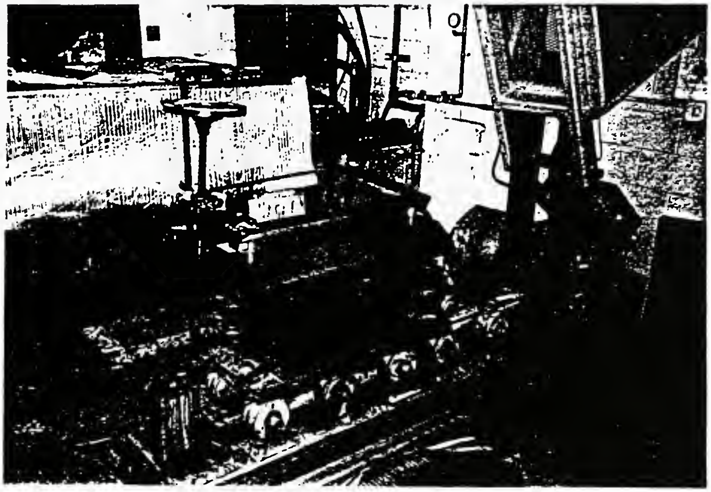

Figure 7.1 Purdue Linear Compactor and Infrared Heater

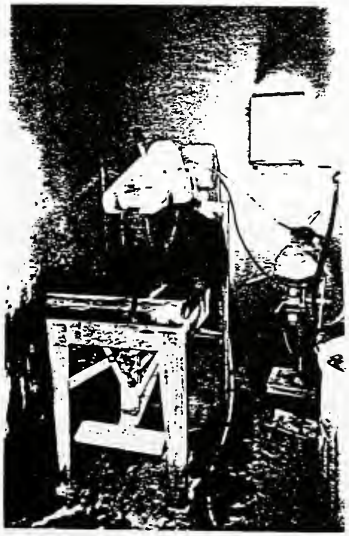

Figure 7.2 Concrete Saw

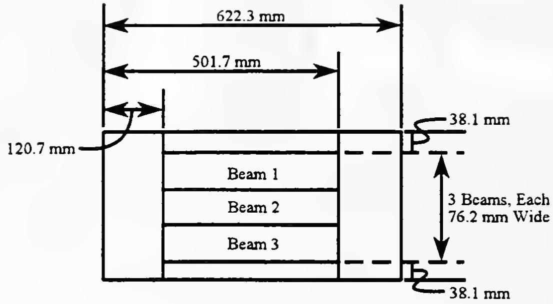

Figure 7.3 First Phase of Saw Cutting Beams, Top View

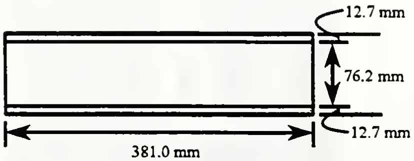

Figure 7.4 Second Phase of Saw Cutting Beams, Side View

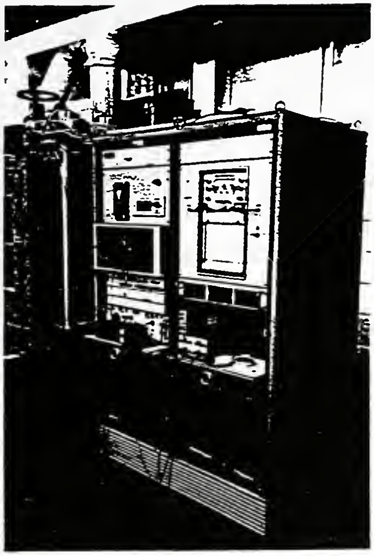

Figure 7.5 MTS Test System

Figure 7.6 Repeated Flexural Frame in the Environmental Chamber

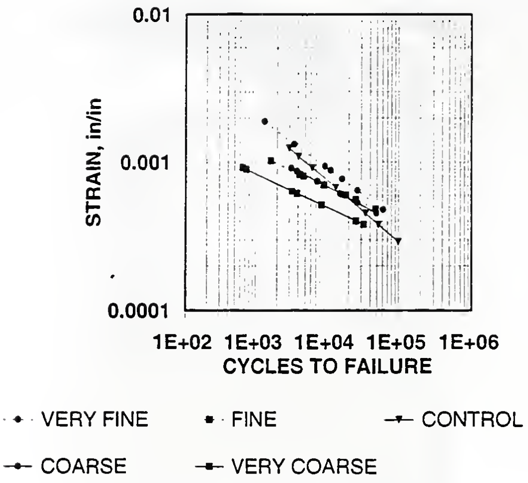

Figure 7.7 Flexural Fatigue Prediction Results, Gravel Surface Mixture

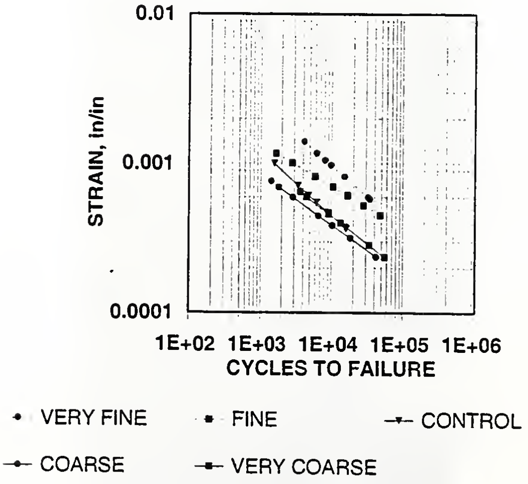

Figure 7.8 Flexural Fatigue Prediction Results, Gravel Binder Mixture

CHAPTER 8. LABORATORY ACCELERATED WHEEL TRACK TESTING

8.1 Introduction

In general, fatigue testing showed that the fine and very fine levels of segregation performed better than the control mix and the coarse and very coarse levels of segregation performed poorer. However, the fine level of segregation for the gravel surface mixture did perform poorer than the control level of segregation. As a result, the coarse levels of segregation would control to relative fatigue performance. For this reason, laboratory wheel track device (WTD) tests were performed on the very coarse, coarse, and control mixtures for both limestone and gravel mixtures.

Binder and surface mixtures for both aggregate types were tested with the WTD. The characteristics of these mixtures were discussed in Chapter 4. The intent of this testing was to determine the relative reduction in performance of coarsely segregated mixtures due to wheel track testing in a hot, wet environment. The following discusses the testing apparatus, sample preparation, test results and analysis.

8.2 Test Apparatus

8.2.1 Purdue University Wheel Test Device

The Purdue University Wheel Test Device (PTD) was used for laboratory wheel

testing of the mixtures. The PTD design was initially developed after certain features of the Hamburg Steel Wheel Tester (HSWT; Hamburg Road Authority, 1992). However, the final design included a number of modifications and features that were unique (Habermann, 1994). The PTD was designed to test larger specimens, 622 mm by 305 mm by 127 mm, verses the smaller HSWT specimens, 305 mm by 305 mm by 127 mm (Hamburg Road Authority, 1992). The HSWT steel wheel is moved through a crank connected to a flywheel which produces a constantly varying velocity. The maximum velocity occurs in the center of the test specimen. Furthermore, the HSWT rut depth measurements are taken only at the center of the specimen. The PTD uses air cylinders to operate at a constant speed over the longitudinal center of specimens with location and number of rut depth measurements being user specified. These rut depth measurements can be made in the center of specimen, at the maximum rut depth, the average about the specimen center or the average about the maximum rut depth location. Frequency of measurement is also user specified. Table 8.1 provides a list of operating characteristics for the PTD and HSWT. In summary, the PTD is a flexible test apparatus with a number of user specified test parameters.

8.3 Sample Preparation

Samples were prepared in a multi-step process. This process included:

1. Drying aggregate to a constant weight,
2. Sieving aggregate into stockpiles by size,
3. Recombining aggregate into individual pans according to specimen

gradation, density and asphalt content,

4. Heating combined aggregate and asphalt to the predetermined mixing temperature based on asphalt viscosity,
5. Mixing aggregate and asphalt,
6. Curing mixture for approximately one hour,
7. Preheating the Purdue Linear Compactor (PLC) mold to the compaction temperature using an infrared heater shown in Figure 8.1,
8. Compacting specimens with the PLC to the desired density and thickness (approximately 38mm for surface and 51mm for binder mixtures) as discussed in Chapter 4,
9. Allowing slabs to cool prior to removal from the PLC mold,
10. Measuring the slab heights at eight locations as shown in Figure 8.2 and then determine their weights,
11. Cutting samples in half using the concrete saw as previously shown in Figure 6.2,
12. Placing the front half of the slab (relative to the PLC) in the right side of the PTD, grouting the sample in place with plaster-of-paris and then installing the back half of the slab in the left side of the PTD in the same way.

After the plaster-of-paris cured (approximately 30 minutes), the PTD water reservoir was

filled until the water was approximately 10 mm over the top of the samples. The water was then heated to the test temperature, 60° C for surface and 57.5° C for binder mixtures, and the samples conditioned for 20 minutes. This is all done automatically based on the user specified test conditions entered in the control software.

8.4 Test Parameters

The binder and surface mixture samples were tested under the same conditions with the exception of temperature. The surface samples were tested at 60° Celsius and the binder samples at 57.5° Celsius. This is the expected maximum pavement temperature the two mix types would be exposed to in Indiana (Gupta, 1987). This assumes that the binder mix has a typical 38 mm surface course overlay. The test conditions were as follows:

1. Hot/wet environment at the respective temperatures.
2. The right side (front half of the slabs) was tested with a load of 565 kPa gross contact pressure and the left side (back half of the slabs) was tested with a load of 621 kPa. This was achieved with a tire pressure of 862 kPa and wheel loads of 150 kg on the right side and 175 kg on the left side.
3. The speed was a constant 0.33 m/s.
4. Rut depth measurements were taken at 10 locations about the specimen center. These measurements were made at a 10 mm spacing. Measurements were made every 250 wheel passes or

until failure. Failure was defined as a 25mm rut depth for the average of these ten rut depth measurements. If the specimen reached 20,000 wheel passes without achieving a 25mm rut depth, the test was automatically stopped.

Figures 8.3 and 8.4 show the contact area of the two pneumatic tires under their 150 and 175 kg loads, respectively. Of note is that the net contact pressure, the load divided by the contact area of just the tread, is approximately equal to the tire pressure.

8.5 Design of Experiment

Only the control, coarse, and very coarse levels of segregation were tested in the PTD. In the fatigue tests, the finer levels of segregation performed better than the coarser levels of segregation. In preliminary wheel track testing utilizing a steel wheel and 75 mm thick surface gravel specimens, the performance of both fine and coarse levels of segregation was about the same (Williams et al., 1996). Therefore with both fatigue and rutting considered, the coarser levels of segregation would control the performance. Thus, the fine and very fine levels of segregation were not wheel track tested. Table 8.2 outlines the design of the experiment. Tables 8.3 - 8.6 show the sample density, asphalt content, and percent air voids. The percent air voids is based on the volumetric density.

8.6 Test Results

The wheel tracking test results are summarized in Tables 8.7 through 8.10 and in Figures 8.5 through 8.40 for both aggregate types and sizes.

8.7 Analysis

Statistical analysis was performed on wheel track test data in a two-step process. The first step was defining the rate of deformation, creep and stripping rates. The second step was statistically determining the effects of the test conditions and level of segregation on mixtures.

The most basic result from wheel track testing is rate of deformation. Rate of deformation is the final rut depth divided by the corresponding number of wheel passes and is expressed as mm per wheel pass (mm/wp).

Creep rate is the rate at which a slab experiences permanent deformation without the compounding effect of moisture. This is best represented in Figure 8.5, where both specimens tested at 621 and 565 kPa experienced pure creep. Thus, the creep rate is the deformation due to creep of a specimen divided by the number of wheel passes. Creep rates were statistically determined by best fit of the data with respect to linear regression analysis.

Stripping rate is defined similar to creep rate. Figure 8.29 shows two samples tested at 621 and 565 kPa contact pressure, respectively, that demonstrate pure stripping. The best fit linear regression equation of data defined the stripping rates. Like creep rate, stripping rate is the rate of deformation when stripping occurs and is expressed as mm of rut depth per wheel pass. Tables 8.7 through 8.10 summarize rate of deformation, creep and stripping rates, and stripping inflection points for test samples. The intersection of

the creep and stripping slopes is referred to as the stripping inflection point.

The second step in statistical analysis of wheel track test data was performing analysis of variance (ANOVA) using SAS (SAS Institute, 1991). The following equation represents the split-plot design used to examine the rate of deformation, creep and stripping rates.

$$Y = u + LOS_i + CP_j + LOS(SAM)_{I(k)} + LOS \times CP_{ij} + CP \times LOS(SAM)_{ij(k)} + Error \qquad (1)$$

where:

Y = Rate of Deformation, Creep Rate, Stripping Rate, Stripping Inflection Point

LOS = Level of Segregation (control, coarse, very coarse),

CP = Contact Pressure (565 kPa, 621 kPa), and

SAM = Sample (1,2,3......, 9).

The $LOS(SAM)_{ik}$ term was used as the error term to test the level of segregation, LOS_i, for statistical significance. The $CP*LOS(SAM)_{ij(k)}$ term was used as the error term to test the contact pressure, CP_j, and the interaction term between level of segregation and contact pressure, $LOS*CP_{ij}$, for statistical significance. The results of the analyses are summarized in Tables 8.11 through 8.13.

8.7.1 Gravel Surface Mixture

Data for gravel surface mixture data included of rate of deformation, creep and

stripping rates, and stripping inflections. Of the samples tested, more than half did not experience stripping. No analysis for the stripping rates and stripping inflection points were performed because of the limited samples size per test cells.

The rate of deformation ANOVA shows that only the contact pressure is significant for an alpha = 5 percent. The average rate of deformation for samples tested with the 565 and 621 kPa contact pressures were 0.00037422 and 0.00052144 mm per wheel pass, respectively. A sample tested with a higher contact pressure would be expected to have a higher rate of deformation than a lower contact pressure. ANOVA of the creep rate shows none of the variables to be statistically significant.

8.7.2 Limestone Surface Mixture

Data for the limestone surface mixture included rate of deformation, creep and stripping rates, and stripping inflection points. Like the gravel surface mixture, the limestone surface mixture had limited sample size per cell for stripping rates and stripping inflection points. Thus, no analysis for stripping rate was performed.

The rate of deformation ANOVA shows the contact pressure and the interaction between the level of segregation and contact pressure to be significant for an alpha = 5 percent. The level of segregation was significant for an alpha = 7 percent. The mean rate of deformation for the control, coarse, and very coarse levels were 0.0020697, 0.0001892, 0.0003990 mm of rut depth per wheel pass, respectively. The coarse and very coarse levels of segregation performed better than the control mix which was not expected. One explanation of this result is that for the gradation, the selected optimum

asphalt content was low. Consequently, there was insufficient asphalt coating of the finer material in the control mix. This would make the control mix more susceptible to moisture damage or stripping. Every control sample did experience stripping.

The average rate of deformation for the 565 and 621 kPa contact pressures were 0.0007022 and 0.0010697 mm of rut depth per wheel pass, respectively. Like the gravel surface mixture, higher contact pressure produced a higher rate of deformation.

ANOVA of the creep rate data found the contact pressure and the interaction between the level of segregation and contact pressure to be significant for alpha = 5 percent. The average creep rates for the 565 and 621 kPa contact pressures were 0.0007022 and 0.0010697 mm of rut depth per wheel pass, respectively. As expected, higher contact pressure yielded a higher creep rate.

8.7.3 Gravel Binder Mixture

Data for the gravel binder mixture data consisted of rate of deformation, creep rates, and stripping rates, and stripping inflection points. A few of the samples did not experience creep and stripping, thus not all of the cell sample sizes are equal.

ANOVA of the rate of deformation and creep rates found none of the variables to be statistically significant for alpha = 5 percent. This indicates that the gravel mixtures are very susceptible to stripping/rutting. It is a characteristic of the gravel, i.e. rounded, low crushed faces or mineralogical.

ANOVA of the stripping rate found the level of segregation was significant at higher than alpha = 5 percent. The average rate of stripping for the very coarse level was

0.043166 mm of rut depth per wheel pass while that of the coarse and control levels were 0.004201 and 0.004115 mm of rut depth per wheel pass, respectively. This indicates that coarsely segregated mixtures are sensitive to moisture once failure begins. Analysis of the stripping inflection points yielded a model with an F-value of 2.18, showing that use of stripping inflection points is not appropriate in evaluating mixtures.

8.7.4 Limestone Binder Mixture

Data for the limestone binder mixture data consisted of rate of deformation and creep rates for nearly all samples tested. The sample sizes within the test cell were unbalanced for the creep rate data because two of the samples did not experience creep. Like the surface mixtures, the limestone binder mixture had very low samples sizes within the test cells for the stripping rate and stripping inflection points. Thus, ANOVA was not performed for the stripping rates and stripping inflection points.

ANOVA of the rate of deformation found the level of segregation was the only statistically significant variable at alpha = 8 percent. ANOVA of the creep rates found no significant variables. The lack of significance with the contact pressure was not expected because at the control and coarse levels of segregation, exclusivity of failure did not occur at the higher 621 kPa contact pressure. This resulted in very slight differences in the performance at the control and coarse levels of segregation.

8.8 Effect of Segregation on Wheel Track Testing Performance

The effect of level of segregation on the performance of a mixture due to wheel

track testing was examined. A rut depth level of 12.7 mm was adopted for evaluating performance. This depth was selected because with a normal highway surface it would retain water. This retained water would create possible hydroplaning of fast moving vehicles, jeopardizing the safety of the traveling public (Shahin, M.Y., and Kohn, S.D., 1979). However, in these tests only the permanent deformation in the wheel path was measured. As a result, the uplift outside the wheel path that occurs on actual pavements was not included. More recently (Pan, 1996) total rut depth (TRD) has been measured along with the wheel track rut depth (WTRD). These data was used to develop a relationship to estimate the TRD and has a goodness of fit of 0.92. The relationship follows.

$$\mathrm{WTRD} = 0.65 \times \mathrm{TRD} + 1.56 \qquad (2)$$

where:

TRD = Total Rut Depth, mm

WTRD = Wheel Track Rut Depth, mm.

A 12.7 mm total rut depth would then be a 6.6 mm wheel track rut depth using equation 2.

The failure criteria of 6.6 mm for the wheel track rut depth allows for the relative performance evaluation of the gravel binder mixture levels of segregation at both tested contact pressures (565 and 621 kPa). At the 565 kPa contact pressure, the coarse level of segregation performed 65.7 percent better than the control while the very coarse

performed 49.0 percent poorer than the control. Similar performance resulted with the 621 kPa contact pressure. The coarse level of segregation performed 48.9 percent better than the control mixture at the 565 kPa contact pressure while the very coarse level of segregation performed 73.3 percent poorer than the control under the 621 kPa. Examination of the performance between the two contact pressures at different levels of segregation for the gravel binder mixture shows the higher contact pressure causes progressively poorer performance with coarser segregation. The 621 kPa versus the 565 kPa contact pressure resulted in a reduction in performance of 34.6, 41.2, and 65.8 percent for the control, coarse, and very coarse levels of segregation, respectively. These results are summarized in Table 8.14.

Table 8.1 PTD and HSWT Operating Characteristics

Parameter	PURWheel Test Device	Hamburg Wheel Track Tester
Speed	0.20 m/s to 0.40 m/s	Sinusoidal with a maximum of 0.33 m/s
Load	500 N to 1900 N	Up to 697 N
Maximum Specimen Size	622 mm×305 mm×127 mm	305 mm×305 mm×127 mm
Type of Wheel	Steel wheel up to 100 mm wide or pneumatic tire with tire pressure up to 862 kPa	47 mm wide Steel wheel
Rut Depth Measurement Location	Anywhere along specimen with the number of measurements specified	Center of sample
Frequency of Measurement	User specified. from every 1 to maximum number of wheel passes	Every 250 wheel passes
Environmental Condition	Hot/Wet or Hot/Dry	Hot/Wet
Wheel Wander	Distribution is user specified	No
Temperature	25 to 60 degrees Celsius	50 degrees Celsius
Data Collection	Automated	Automated

Table 8.2 Wheel Track Testing Design of Experiment

		Level of Segregation								
		Control			Coarse			Very Coarse		
	Sample	1	2	3	4	5	6	7	8	9
Contact Pressure	565	X	X	X	X	X	X	X	X	X
	621	X	X	X	X	X	X	X	X	X

Table 8.3 Gravel Surface Sample Characteristics

Level of Segregation	Sample	Bulk Specific Gravity	Percent Air Voids
Control	1	2.271	8.49
	2	2.260	9.35
	3	2.268	10.04
Coarse	4	2.234	10.92
	5	2.242	11.30
	6	2.219	10.92
Very Coarse	7	2.024	22.10
	8	2.049	20.93
	9	2.133	16.95

Table 8.4 Limestone Surface Sample Characteristics

Level of Segregation	Sample	Bulk Specific Gravity	Percent Air Voids
Control	1	2.259	11.49
	2	2.294	9.99
	3	2.378	6.41
Coarse	4	2.317	9.22
	5	2.325	8.88
	6	2.315	9.30
Very Coarse	7	2.130	17.52
	8	2.091	19.39
	9	2.147	16.79

Table 8.5 Gravel Binder Sample Characteristics

Level of Segregation	Sample	Bulk Specific Gravity	Percent Air Voids
Control	1	2.214	12.56
	2	2.198	13.24
	3	2.241	11.35
Coarse	4	2.114	17.98
	5	2.108	18.18
	6	2.146	16.38
Very Coarse	7	1.961	25.14
	8	1.933	26.59
	9	1.922	27.17

Table 8.6 Limestone Binder Sample Characteristics

Level of Segregation	Sample	Bulk Specific Gravity	Percent Air Voids
Control	1	2.259	11.59
	2	2.235	12.62
	3	2.264	11.37
Coarse	4	2.141	17.51
	5	2.135	17.79
	6	2.144	17.36
Very Coarse	7	1.939	26.10
	8	1.932	24.82
	9	1.972	24.85

Table 8.7 Gravel Surface Wheel Track Test Results Summary

Level of Segregation	Sample	Contact Pressure (kPa)	Creep Rate (mm/wp)	Stripping Rate (mm/wp)	Stripping Inflection Point, wp	Rate of Deformation (mm/wp)	Number of Wheel Passes	Final Rut Depth (mm)
Control	1	621	0.000163	N/A	N/A	0.000280	20,000	5.60
	1	565	0.000106	N/A	N/A	0.000176	20,000	3.52
	2	621	0.000214	N/A	N/A	0.000294	20,000	5.88
	2	565	0.000069	N/A	N/A	0.000154	20,000	3.07
	3	621	0.000323	N/A	N/A	0.000432	20,000	8.63
	3	565	0.000073	N/A	N/A	0.000152	20,000	3.04
Coarse	4	621	0.000086	N/A	N/A	0.000235	20,000	4.69
	4	565	0.000135	N/A	N/A	0.000183	20,000	3.66
	5	621	0.000077	N/A	N/A	0.000164	20,000	3.28
	5	565	0.000063	N/A	N/A	0.000139	20,000	2.77
	6	621	0.000037	N/A	N/A	0.000083	20,000	1.65
	6	565	0.000065	N/A	N/A	0.000135	20,000	2.70
Very Coarse	7	621	0.000656	N/A	N/A	0.000761	20,000	15.21
	7	565	0.000341	N/A	N/A	0.000431	20,000	8.62
	8	621	0.000247	N/A	N/A	0.000351	20,000	7.01
	8	565	0.000185	N/A	N/A	0.000315	20,000	6.29
	9	621	0.000419	0.007948	2963	0.002093	11,846	24.79
	9	565	0.000286	0.023811	1059	0.001683	15,166	25.52

Table 8.8 Limestone Surface Wheel Track Test Results Summary

Level of Segregation	Sample	Contact Pressure (kPa)	Creep Rate (mm/wp)	Stripping Rate (mm/wp)	Stripping Inflection Point, wp	Rate of Deformation (mm/wp)	Number of Wheel Passes	Final Rut Depth (mm)
Control	1	621	0.002154	0.007280	2636	0.004424	5,622	24.87
	1	565	0.001698	0.007161	2883	0.002906	8,788	25.54
	2	621	0.000723	0.007143	3210	0.002020	12,500	25.25
	2	565	0.000333	0.002988	4231	0.000675	20,000	14.05
	3	621	0.000535	0.010850	2226	0.001987	12,750	25.34
	3	565	0.000247	N/A	N/A	0.000406	20,000	8.12
Coarse	4	621	0.000049	N/A	N/A	0.000164	20,000	3.28
	4	565	0.000154	N/A	N/A	0.000230	20,000	4.59
	5	621	0.000091	N/A	N/A	0.000170	20,000	3.06
	5	565	0.000052	N/A	N/A	0.000243	20,000	4.38
	6	621	0.000084	N/A	N/A	0.000170	20,000	3.40
	6	565	0.000075	N/A	N/A	0.000158	20,000	3.16
Very Coarse	7	621	0.000152	N/A	N/A	0.000221	20,000	4.41
	7	565	0.000145	N/A	N/A	0.000229	20,000	4.58
	8	621	0.000250	0.005639	4344	0.000388	18,650	25.58
	8	565	0.000264	N/A	N/A	0.001372	20,000	7.75
	9	621	0.000027	N/A	N/A	0.000084	20,000	1.67
	9	565	0.000040	N/A	N/A	0.000101	20,000	2.02

Table 8.9 Gravel Binder Wheel Track Test Results Summary

Level of Segregation	Sample	Contact Pressure (kPa)	Creep Rate (mm/wp)	Stripping Rate (mm/wp)	Stripping Inflection Point, wp	Rate of Deformation (mm/wp)	Number of Wheel Passes	Final Rut Depth (mm)
Control	1	621	0.005488	0.005488	10453	0.006551	3.810	24.96
	1	565	0.001100	0.001352	2084	0.001739	14.298	25.63
	2	621	0.005994	0.006090	4771	0.006595	3.818	25.18
	2	565	0.002653	0.002665	4787	0.003157	8.036	25.37
	3	621	0.000379	0.004981	3803	0.001336	19.212	25.66
	3	565	0.000291	N/A	N/A	0.000408	20.000	8.15
Coarse	4	621	0.001429	0.005152	5774	0.003163	7.914	25.03
	4	565	0.000938	0.003496	5949	0.001821	14.056	25.60
	5	621	0.001113	0.002879	2565	0.002450	9.694	23.75
	5	565	0.000293	0.009675	8880	0.001300	19.676	25.57
	6	621	0.000427	0.002449	6916	0.001284	19.888	25.54
	6	565	0.000449	0.001552	575	0.000692	20.000	13.84
Very Coarse	7	621	0.005556	0.038189	745	0.017359	1.450	25.17
	7	565	0.001880	0.031813	724	0.006781	3.700	25.09
	8	621	0.003493	0.029449	607	0.001078	2.212	23.84
	8	565	0.000878	0.039631	528	0.005651	4.350	24.58
	9	621	N/A	0.069795	N/A	0.069795	390	27.22
	9	565	0.002672	0.050116		0.010735	2.598	27.89

Table 8.10 Limestone Binder Wheel Track Test Results Summary

Level of Segregation	Sample	Contact Pressure (kPa)	Creep Rate (mm/wp)	Stripping Rate (mm/wp)	Stripping Inflection Point. wp	Rate of Deformation (mm wp)	Number of Wheel Passes	Final Rut Depth (mm)
Control	1	621	0.000462	N/A	N A	0.000910	20.000	18.20
	1	565	0.000354	N/A	N/A	0.000552	20.000	11.04
	2	621	0.000326	N/A	N/A	0.000490	20.000	9.79
	2	565	0.000134	N/A	N A	0.000251	20.000	5.02
	3	621	0.000154	N/A	N A	0.000267	20.000	5.34
	3	565	0.000138	N A	N/A	0.000251	20.000	5.01
Coarse	4	621	0.000871	0.003787	5468	0.001998	12.750	25.47
	4	565	0.000245	N/A	N A	0.000333	20.000	6.66
	5	621	0.001662	0.008058	2552	0.002632	9.426	24.81
	5	565	0.000046	N/A	N/A	0.000197	20.000	3.94
	6	621	0.000153	N/A	N A	0.000269	20.000	5.37
	6	565	0.000126	N/A	N/A	0.000187	20.000	3.74
Very Coarse	7	621	0.007506	0.032844	668	0.029508	914	26.97
	7	565	0.001319	0.024467	1004	0.006277	4.126	25.90
	8	621	0.000474	0.032850	740	0.002586	9.532	24.65
	8	565	0.000297	N A	N/A	0.000440	20.000	8.79
	9	621	N/A	0.011640	N A	0.026431	1.048	27.70
	9	565	N A	0.009843	N A	0.021880	1.250	27.35

Table 8.11 Summary of Statistical Analysis for Rate of Deformation

	F-Statistic (Pr > F)			
Test Parameter	Surface Gravel	Surface Limestone	Binder Gravel	Binder Limestone
LOS	2.36 (0.1749)	4.57 (0.0623)	2.06 (0.2089)	4.19 (0.0728)
CP	11.62 (0.0143)	11.00 (0.0161)	1.80 (0.2286)	2.98 (0.1348)
LOS*CP	2.90 (0.1313)	25.86 (0.0011)	1.05 (0.4057)	1.90 (0.2295)

Table 8.12 Summary of Statistical Analysis for Creep Rate

	F-Statistic (Pr > F)			
Test Parameter	Surface Gravel	Surface Limestone	Binder Gravel	Binder Limestone
LOS	3.00 (0.1252)	2.85 (0.1351)	0.83 (0.4994)	1.83 (0.2530)
CP	1.96 (0.2114)	28.48 (0.0018)	0.82 (0.4160)	3.31 (0.1284)
LOS*CP	0.93 (0.4454)	35.07 (0.0005)	0.73 (0.5362)	1.55 (0.2998)

Table 8.13 Summary of Statistical Analysis for Stripping Rate

	F-Statistic (Pr > F)
Test Parameter	Binder Gravel
LOS	20.42 (0.0021)
CP	0.50 (0.5104)
LOS*CP	0.37 (0.7089)

Table 8.14 Gravel Binder Wheel Track Performance

Level of Segregation	Wheel Passes to Failure. 565 kPa Contact Pressure	Performance Relative to the Control at 565 kPa. Percent	Wheel Passes to Failure. 621 kPa Contact Pressure	Performance Relative to the Control at 621 kPa. Percent	Performance Between 565 kPa and 621 kPa Contact Pressure. Percent
Control	2478	N/A	3789	N/A	-34.6
Coarse	3690	+65.7	6280	+48.9	-41.2
Very Coarse	662	-49.0	1934	-73.3	-65.8

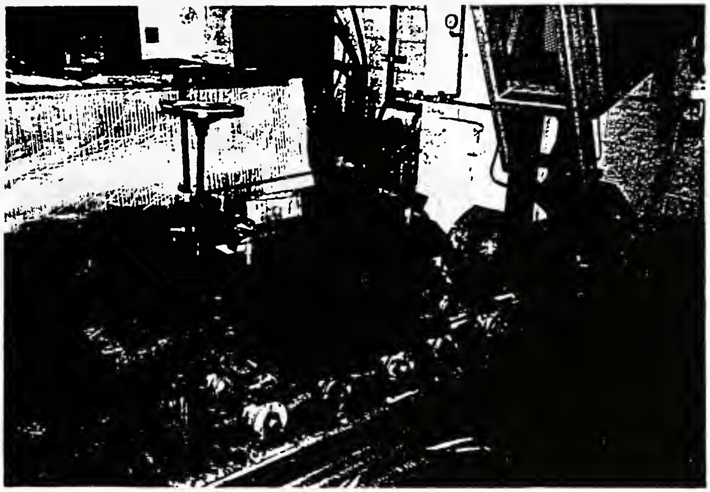

Figure 8.1 Purdue Linear Compactor and Infrared Heater

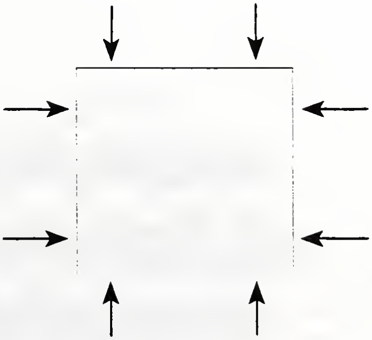

Figure 8.2 Location of Sample Height Measurements From a Planimetric View

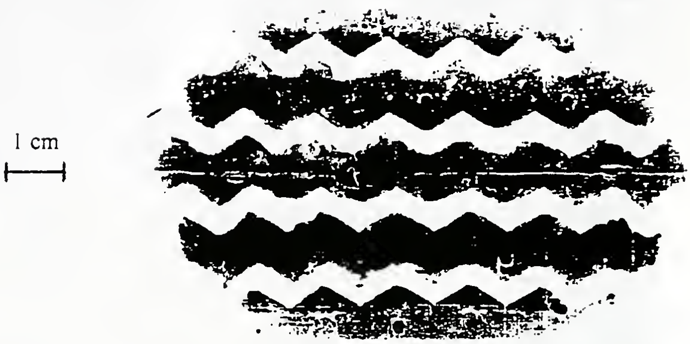

Figure 8.3 Contact Area of 682 kPa Tire Pressure and 150 kg Load

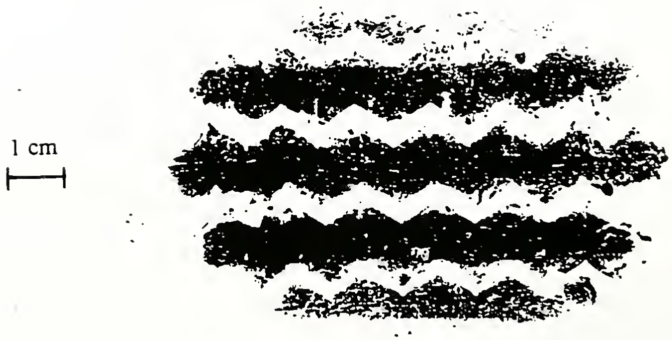

Figure 8.4 Contact Area of 682 kPa Tire Pressure and 175 kg Load

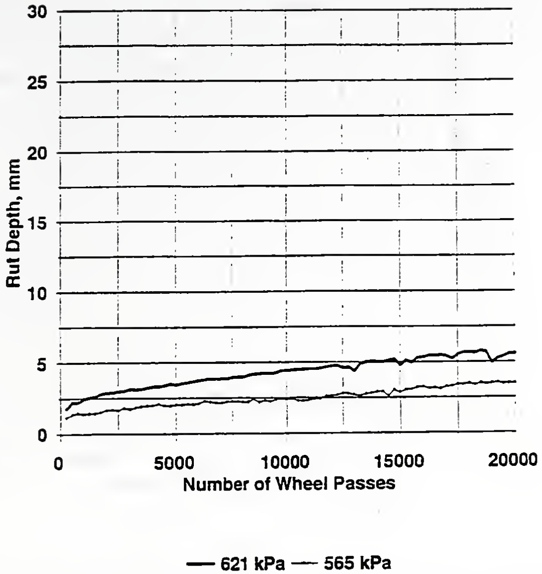

Figure 8.5 Wheel Track Test Results of Gravel Surface Mixture, Control, Sample 1

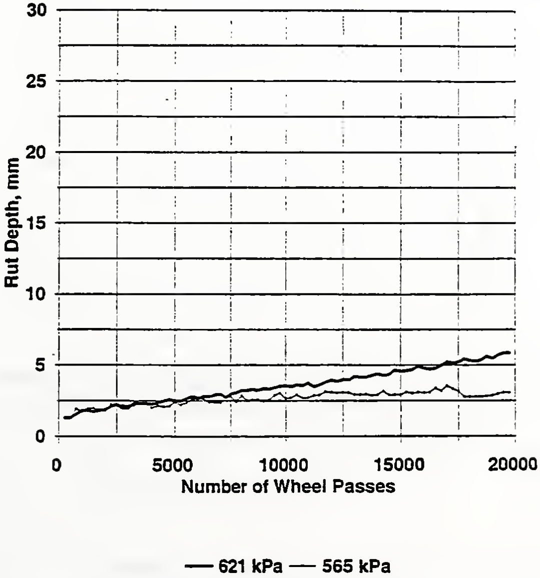

Figure 8.6 Wheel Track Test Results of Gravel Surface Mixture, Control, Sample 2

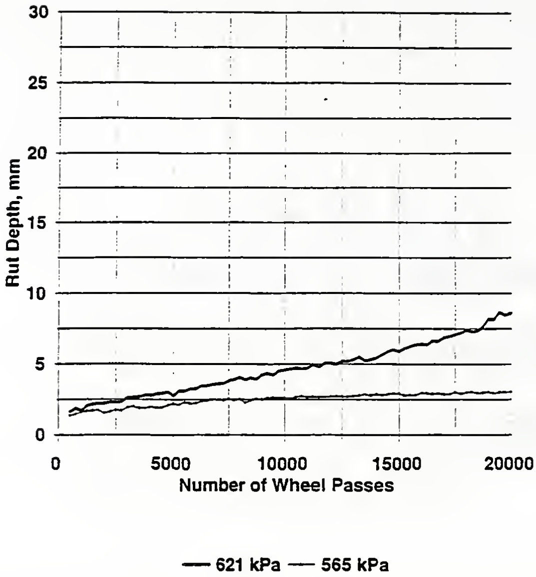

Figure 8.7 Wheel Track Test Results of Gravel Surface Mixture, Control, Sample 3

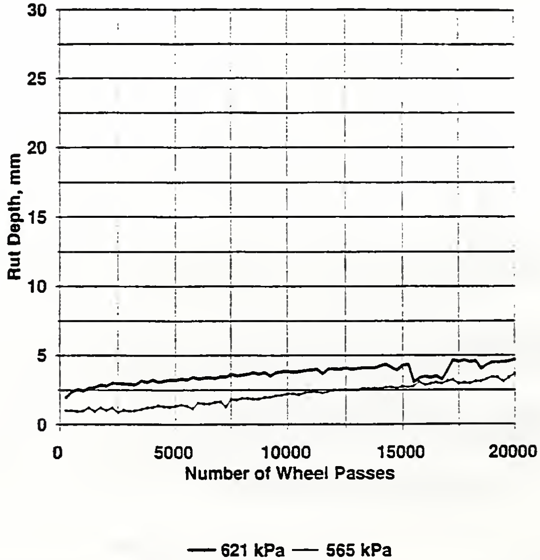

Figure 8.8 Wheel Track Test Results of Gravel Surface Mixture, Coarse, Sample 1

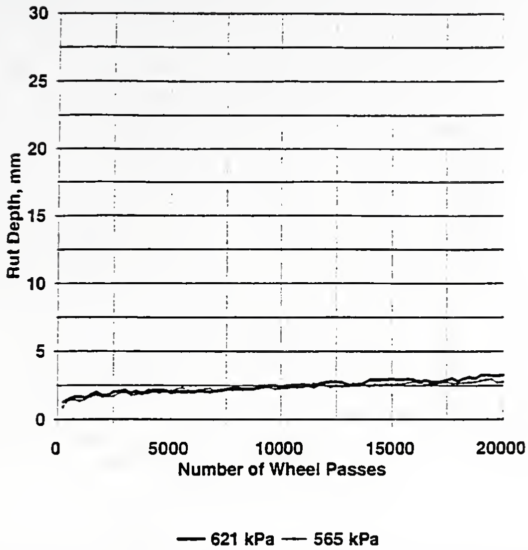

Figure 8.9 Wheel Track Test Results of Gravel Surface Mixture, Coarse, Sample 2

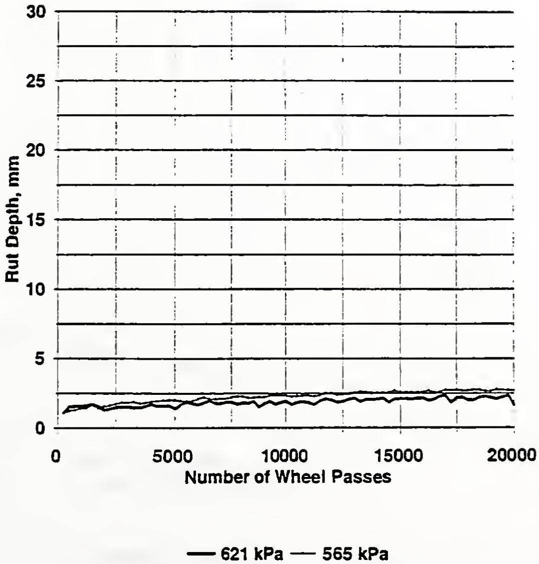

Figure 8.10 Wheel Track Test Results of Gravel Surface Mixture, Coarse, Sample 3

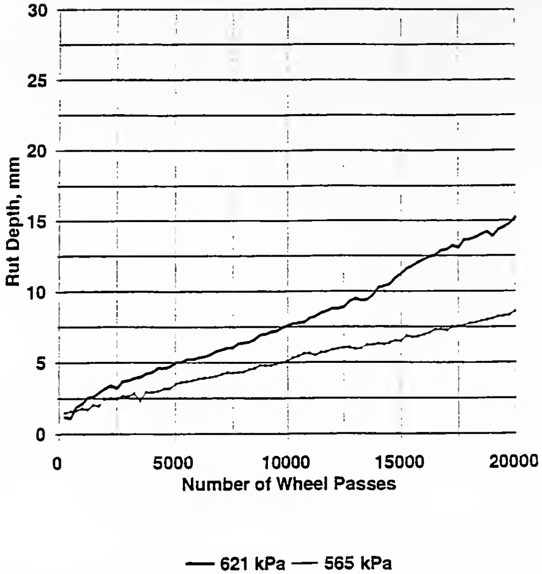

Figure 8.11 Wheel Track Test Results of Gravel Surface Mixture, Very Coarse, Sample 1

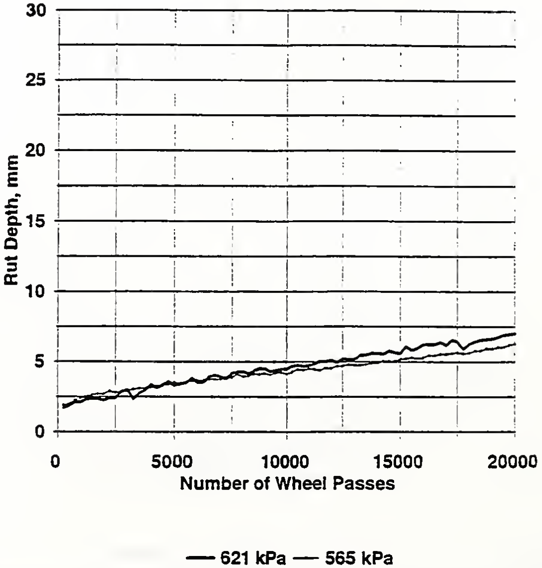

Figure 8.12 Wheel Track Test Results of Gravel Surface Mixture, Very Coarse, Sample 2

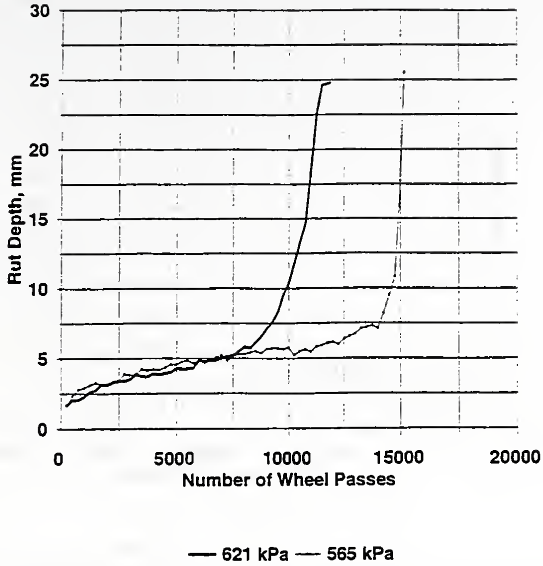

Figure 8.13 Wheel Track Test Results of Gravel Surface Mixture, Very Coarse, Sample 3

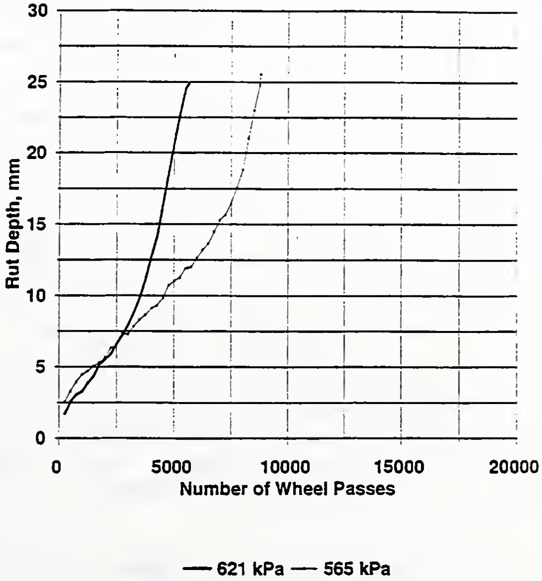

Figure 8.14 Wheel Track Test Results of Limestone Surface Mixture, Control, Sample 1

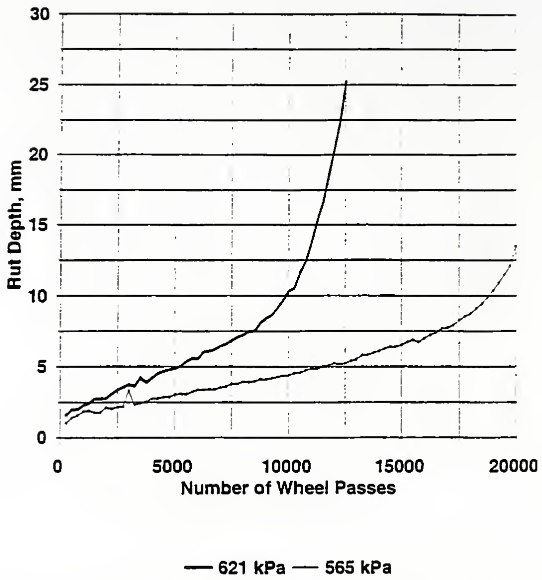

Figure 8.15 Wheel Track Test Results of Limestone Surface Mixture. Control, Sample 2

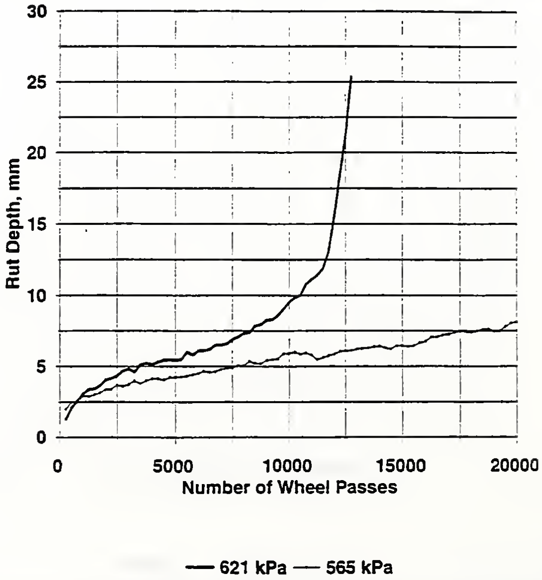

Figure 8.16 Wheel Track Test Results of Limestone Surface Mixture, Control, Sample 3

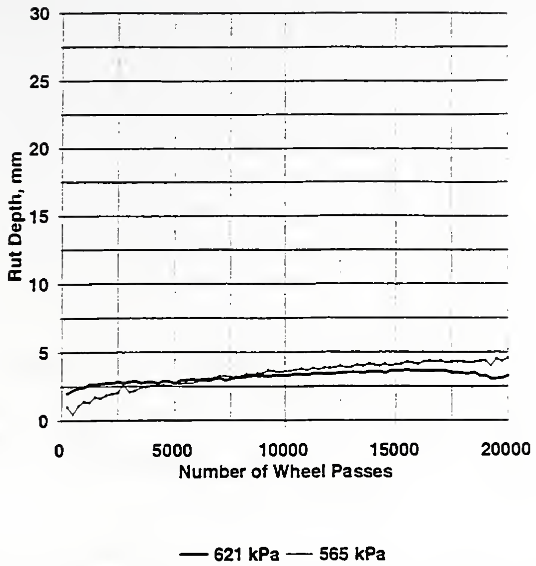

Figure 8.17 Wheel Track Test Results of Limestone Surface Mixture, Coarse, Sample 1

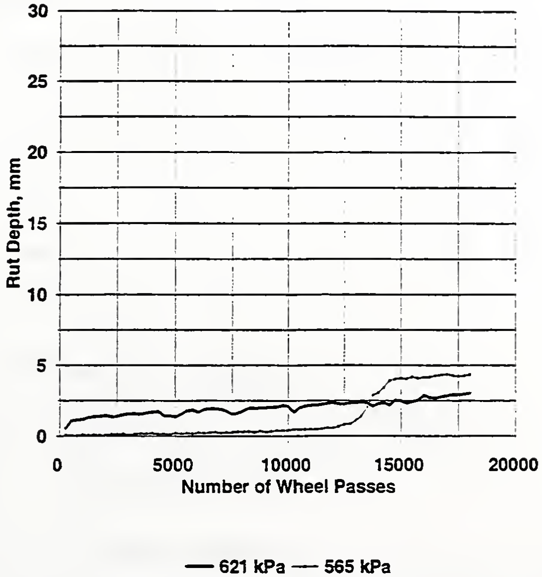

Figure 8.18 Wheel Track Test Results of Limestone Surface Mixture, Coarse, Sample 2

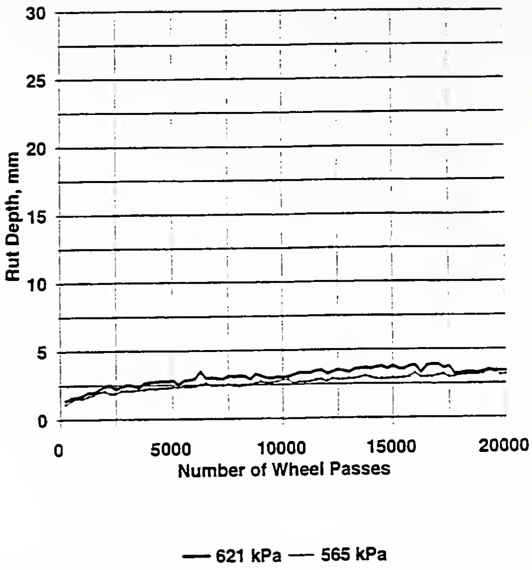

Figure 8.19 Wheel Track Test Results of Limestone Surface Mixture, Coarse, Sample 3

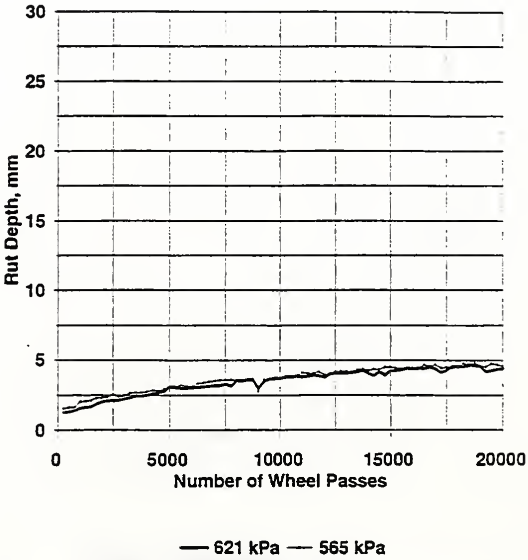

Figure 8.20 Wheel Track Test Results of Limestone Surface Mixture, Very Coarse, Sample 1

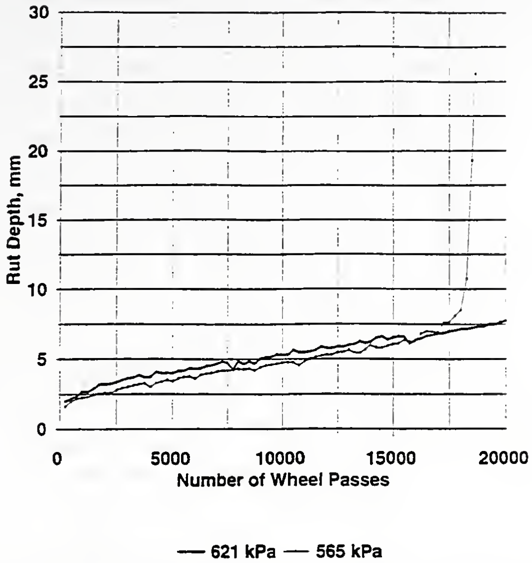

Figure 8.21 Wheel Track Test Results of Limestone Surface Mixture, Very Coarse, Sample 2

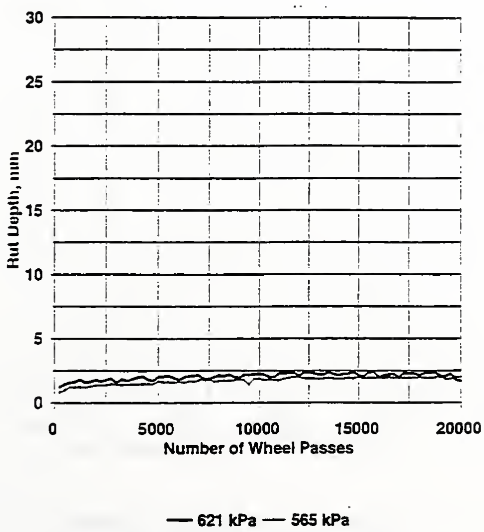

Figure 8.22 Wheel Track Test Results of Limestone Surface Mixture, Very Coarse, Sample 3

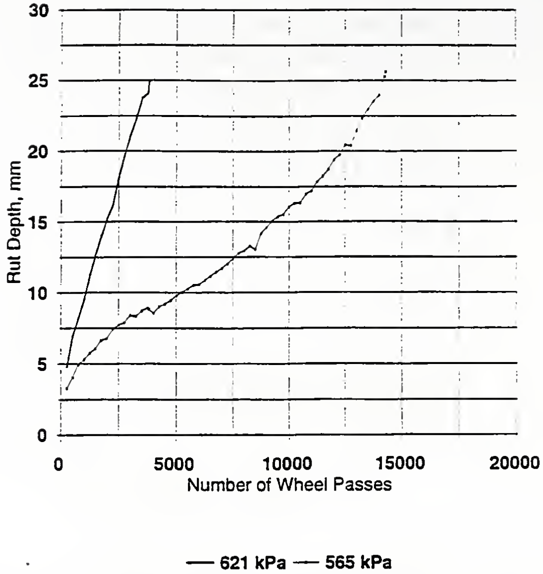

Figure 8.23 Wheel Track Test Results of Gravel Binder Mixture, Control, Sample 1

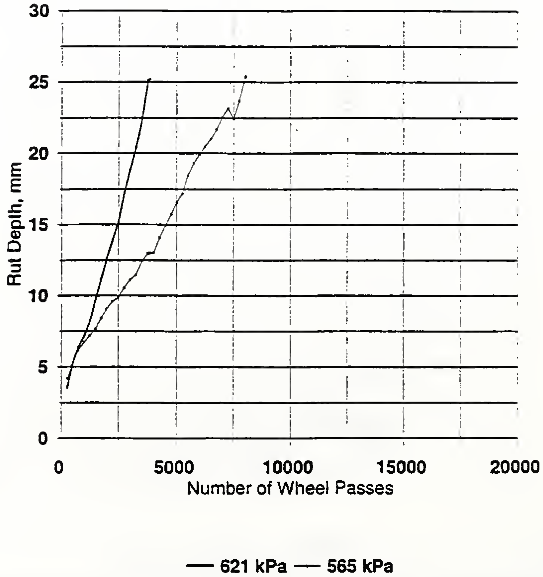

Figure 8.24 Wheel Track Test Results of Gravel Binder Mixture, Control, Sample 2

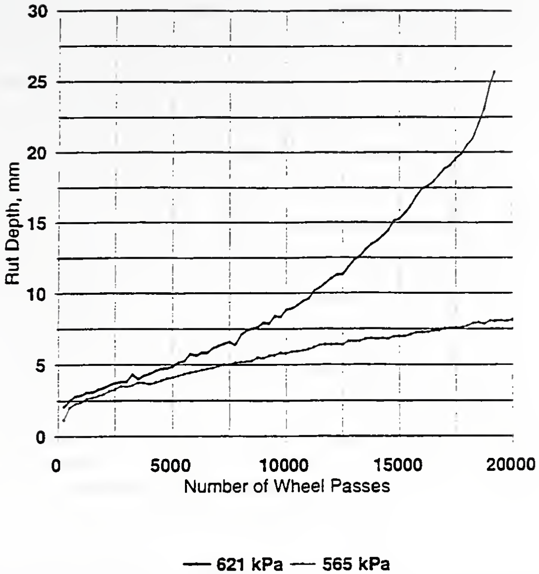

Figure 8.25 Wheel Track Test Results of Gravel Binder Mixture, Control, Sample 3

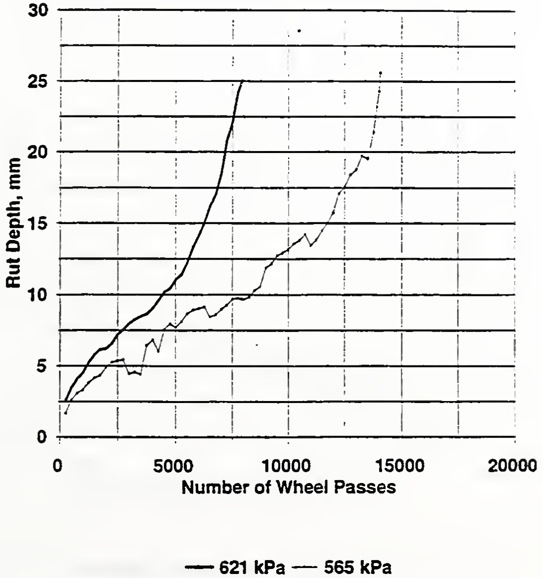

Figure 8.26 Wheel Track Test Results of Gravel Binder Mixture, Coarse, Sample 1

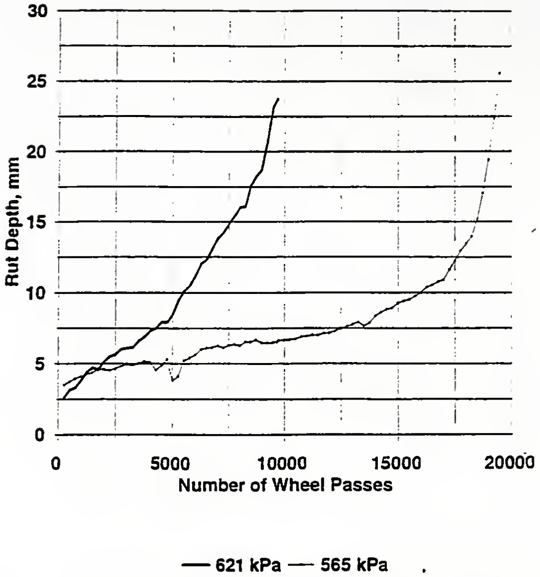

Figure 8.27 Wheel Track Test Results of Gravel Binder Mixture, Coarse. Sample 2

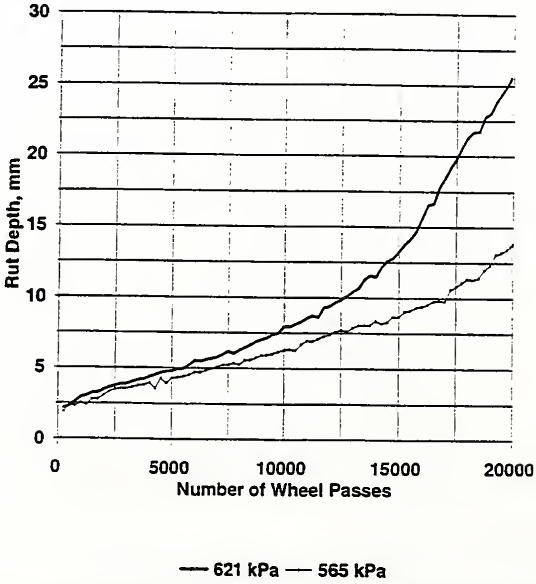

Figure 8.28 Wheel Track Test Results of Gravel Binder Mixture, Coarse, Sample 3

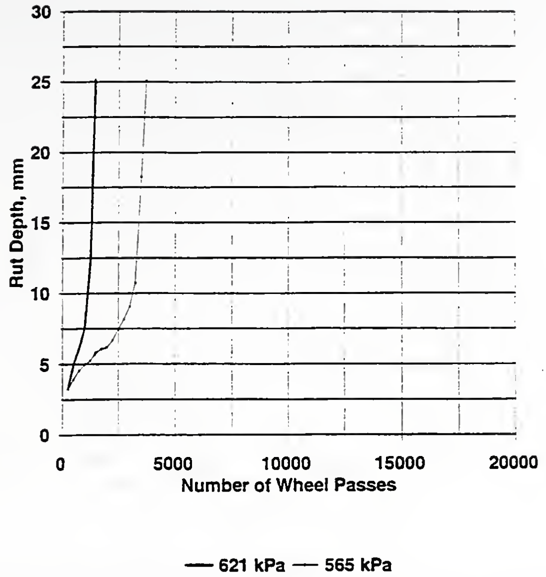

Figure 8.29 Wheel Track Test Results of Gravel Binder Mixture, Very Coarse, Sample 1

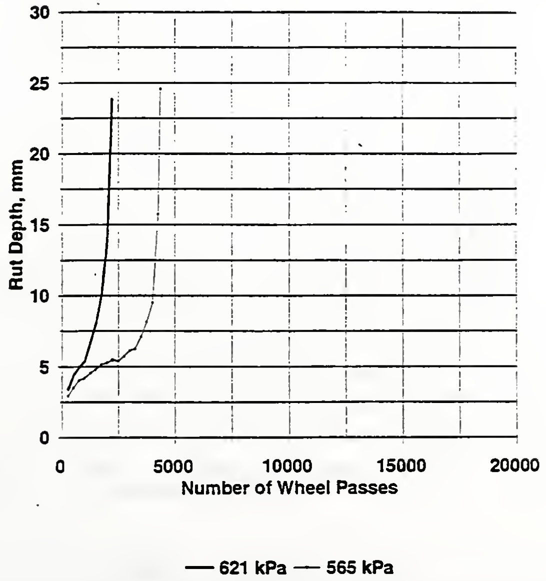

Figure 8.30 Wheel Track Test Results of Gravel Binder Mixture, Very Coarse, Sample 2

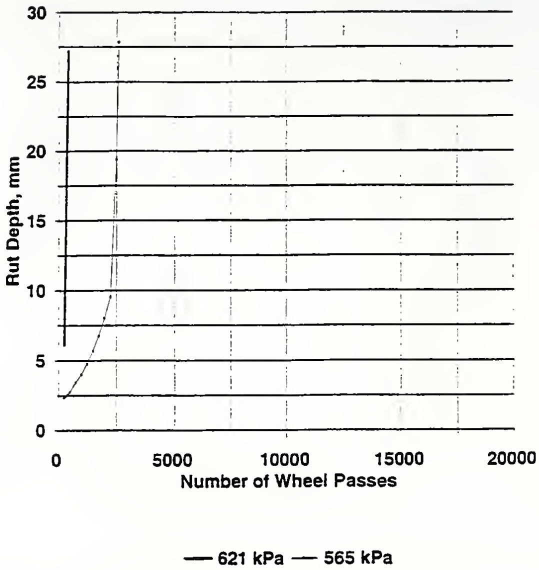

Figure 8.31 Wheel Track Test Results of Gravel Binder Mixture, Very Coarse, Sample 3

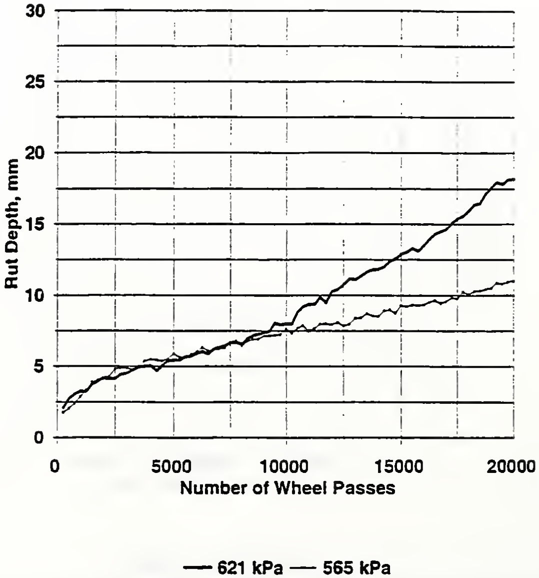

Figure 8.32 Wheel Track Test Results of Limestone Binder Mixture, Control, Sample 1

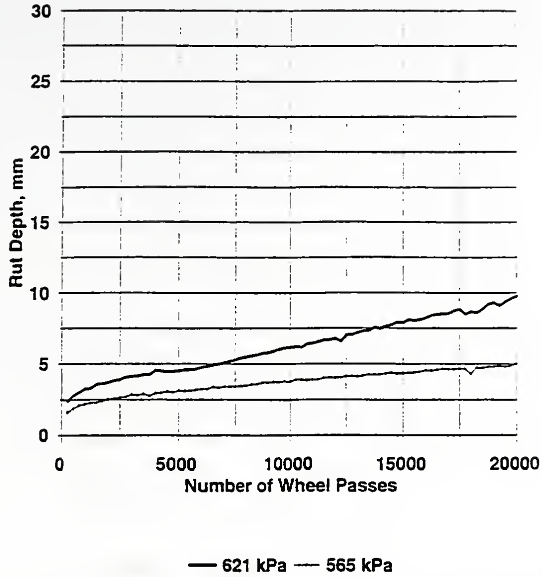

Figure 8.33 Wheel Track Test Results of Limestone Binder Mixture, Control, Sample 2

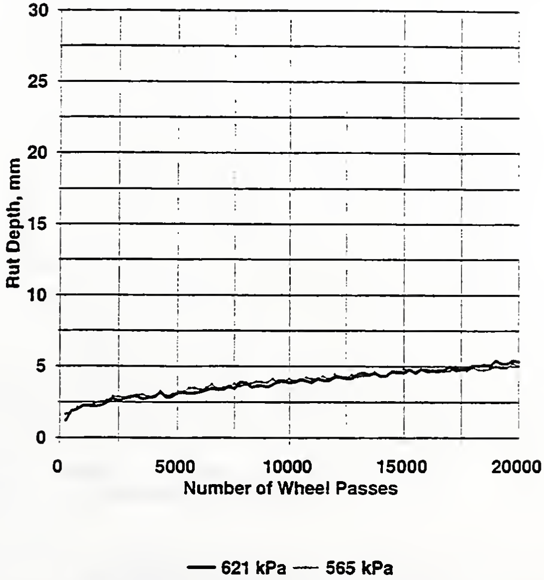

Figure 8.34 Wheel Track Test Results of Limestone Binder Mixture, Control, Sample 3

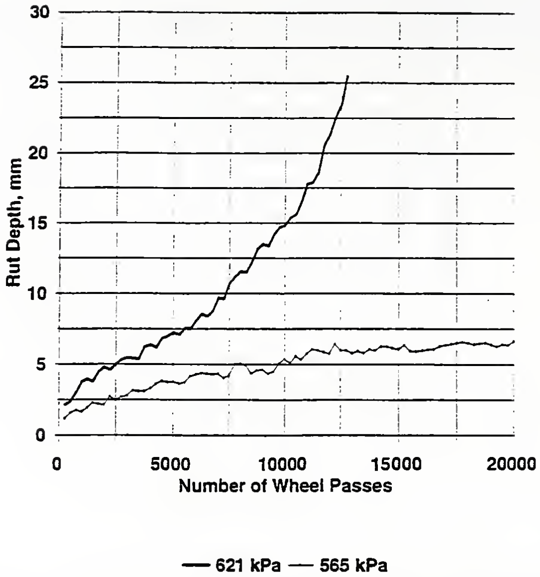

Figure 8.35 Wheel Track Test Results of Limestone Binder Mixture, Coarse. Sample 1

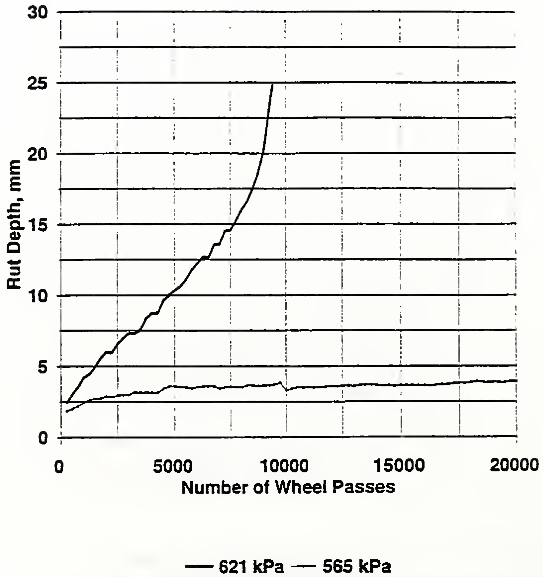

Figure 8.36 Wheel Track Test Results of Limestone Binder Mixture, Coarse, Sample 2

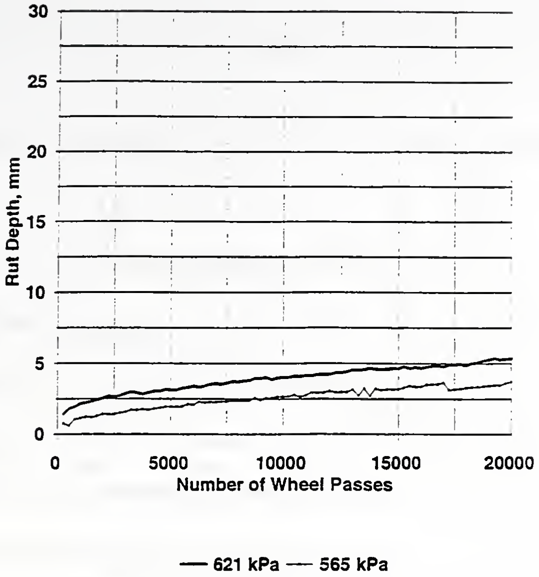

Figure 8.37 Wheel Track Test Results of Limestone Binder Mixture, Coarse, Sample 3

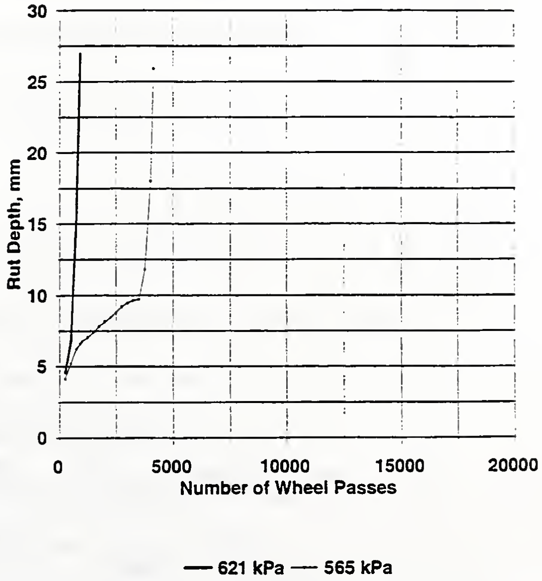

Figure 8.38 Wheel Track Test Results of Limestone Binder Mixture, Very Coarse, Sample 1

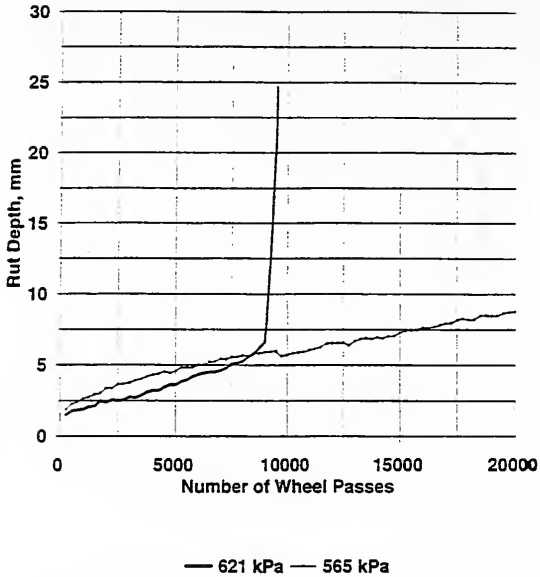

Figure 8.39 Wheel Track Test Results of Limestone Binder Mixture, Very Coarse, Sample 2

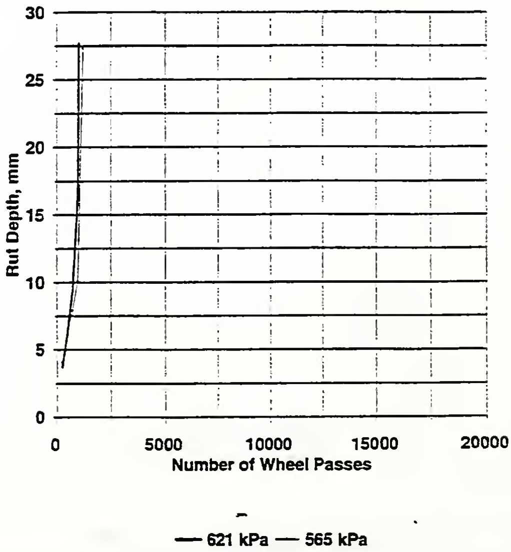

Figure 8.40 Wheel Track Test Results of Limestone Binder Mixture, Very Coarse, Sample 3

CHAPTER 9. CONCLUSIONS AND RECOMMENDATIONS

9.1 Characterization of Segregation

Asphalt mixture segregation is the nonuniform distribution of coarse and fine aggregate components. With segregation there are physical characteristics that are measurably different than the non-segregated mixture. This is true for both fine and coarse segregation. These characteristics include a change in density, asphalt content and air voids. Fine segregation has a lower percentage of air voids, lower density, and higher asphalt content than the non-segregated mixture. Coarse segregation has lower asphalt content and higher percentage of air voids resulting in a dramatically lower density than non-segregated mixtures.

9.2 State of Practice

The survey conducted of State Highway Agencies (SHA) supported the need for a rapid non-destructive testing method for segregation detection. Subjective visual evaluation in combination with extraction and gradations as used by several SHA's would seem to be resource intensive.

Of those states that do utilize a nuclear gauge for detection of segregation, the basis for detection is mainly density differences. Current studies have not shown density variation to be a reliable indicator of segregation as discussed in section 2.3.

The specifications that are used by many agencies concentrate on post-mixing HMA segregation. Segregation also needs to be addressed during mix design, stockpiling and plant operations.

9.3 Non-Destructive Detection of Segregation

9.3.1 Thermal Imaging and Air or Water Permeameter

As discussed in Chapter four, thermal imaging did confirm visual location of segregated areas. However, the technology was not considered effective in locating segregation occurring beneath the surface. Also discussed earlier was the insufficiency of the air permeameter in detecting hidden segregation. This is evident when examining Figures 5.4 through 5.11.

9.3.2 Nuclear Gauge

Results show that the nuclear moisture/density gauge can be used effectively to identify variations in asphalt mixture physical properties that can be attributed to segregation. The results show that the nuclear moisture/density gauge has the potential to be used in the quality control process to identify in place segregation. Results show that a four minute nuclear gauge reading was found to minimize the measurement error of density and moisture (asphalt) content. Readings of shorter duration provide somewhat higher variation.

A bias analysis and subsequent GLM analysis of the correction factors indicated

that degree of segregation had no effect on the nuclear density readings. Results of the GLM analysis also indicated that the nuclear gauge density reading varied with differing base pavement for the limestone mixtures. The combined analysis showed that the nuclear gauge readings varied with the type of aggregate in the mix. The nuclear gauge overpreidcted the densities of the limestone mixes. The combined analysis also showed that mixture type (#11 Surface or #8 Gravel) had no effect on the nuclear gauge density readings.

Both the bias analysis and GLM analysis of the correction factors showed that the nuclear asphalt content readings varied with mixture type, aggregate type, degree of segregation and base pavement. In all cases, the nuclear gauge overpredicted the asphalt contents of the samples. Results show that the nuclear gauge asphalt content reading varied with differing as-mixed asphalt contents.

Correction factors may be used to lessen or eliminate the bias caused by the independent variables of mix type, base pavement and degree of segregation. When these corrections are made to the data, the nuclear gauge provides results which accurately predicted density and asphalt content of the samples.

A discriminant analysis showed that the nuclear moisture/density gauge has the potential to be used effectively to classify a materials degree of segregation. It is important that the potential exhibited by the results of the study be extended and evaluated for field conditions.

It is recommended that future studies include an analysis of the effect of varied asphalt layer thickness on the nuclear gauge density and asphalt content readings. It is

also recommended that the studies should include varied segregated layer thickness as a factor in the design of experiment matrix.

9.3.3 Permittivity

In permittivity measurement, a limited number of samples were examined, and thus no conclusions can be made on an experimental basis. However, the tests results indicate that this technology does exhibit potential to discriminate segregation and should be studied further.

9.4 Conclusions for Field Tests

9.4.1 Sublot Testing Transverse to Laydown Direction

Sublot testing transverse to laydown direction should be performed utilizing four minute nuclear gauge measurements. It is apparent that laydown operations can produce varying levels of segregation transverse to the laydown operation. Because of this transverse variation in the material, the density test results at transverse locations should not be averaged as it would be an average for properties of different materials. With current laydown equipment capability, averaging nuclear gauge measurements should be done only in the longitudinal direction.

9.4.2 Visual Location of Segregation

It has been demonstrated that nuclear gauge testing of visually identified segregated areas is very effective in quantifying segregation and should be implemented. Based upon field testing with four minute nuclear gauge readings of density and moisture (asphalt) content, coarse segregation was identified with perfect accuracy. The following implementation of nuclear gauge testing to confirm visual identified segregation is recommended.

1. A standard background count is taken before use on a daily basis to check gauge operation and allow for source decay. The new count will pass if plus or minus two percent of the moisture average and/or plus or minus one percent of the density average. The operating manual should be consulted to ensure safe operating procedures.
2. The gauge is operated in backscatter mode. Further, the gauge is operated in the soil mode allowing for both density and moisture (asphalt) content measurements.
3. Analysis of coarse segregation is visually identified by an inspector. This area of coarse segregation is defined as an area having considerably more coarse aggregate than the surrounding acceptable mat and contains little or no mastic. Figure 9.1 identifies such an area.
4. A nuclear gauge is placed on the subject location and concurrent four minute readings of density and moisture (asphalt) content are recorded.

5. The density reading is subtracted from the job mix formula target density. This value is referred to as the "Difference in density from the JMF."
6. The moisture (asphalt) content reading is subtracted from the job mix formula target asphalt content. This value is referred to as the "Difference in asphalt content from the JMF."
7. The values obtained in steps 5 and 6 are plotted on Figure 9.2 titled "Visual Coarse Segregation Classification Based on 4 Minute Nuclear Gauge Readings."
8. If the plotted point falls below the 90 percent posterior probability line (90 PP), the location is identified as being coarsely segregated.

9.5 Fatigue Characteristics

The flexural fatigue characteristics of segregated hot mix asphalt pavement is similar to that of non-segregated hot mix. Regression models show that segregated mixtures are generally parallel to non-segregated mixtures when graphed on a log-log scale with strain and number of cycles to failure. Finer levels of segregation exhibited improved fatigue performance, while coarser segregation generally exhibits poorer performance when compared to non-segregated mixtures at the same strain level. This indicates that from a fatigue standpoint, coarse segregation is critical and could lead to premature pavement fatigue failure.

Epps and Monismith (1969) concluded that with a fixed asphalt content, the change in gradation did not affect the fatigue life of mixtures with a 12.5 mm nominal

maximum size aggregate. Their work would be indicative of aggregate segregation prior to combination with asphalt. In this case, the segregated aggregate would be combined with the correct amount of asphalt. The current research would be indicative of segregation of the optimum mixture after mixing. Thus, segregation occurring in aggregate stockpiles, cold feed bins, and/or hot bins is not as detrimental to fatigue life as segregation during mixture storage, transfer, transport and placement.

9.6 Permanent Deformation

Permanent deformation testing during laboratory accelerated wheel track testing indicates that some coarser levels of segregation perform better than the developed control mixtures (no segregation). Limestone mixtures tested tended to produce more consistent results than gravel mixtures. This is likely due to the varying mineralogy of the gravel in samples and/or the variability of the physical characteristics of the gravel (i.e. crushed faces).

The gross contact pressure during wheel track testing was significant when stripping occurred, as evident from the gravel binder tests. During the creep phase of a test and for the overall rate of deformation, the gross contact pressure was also found to be statistically significant for the limestone surface mixtures but not for any of the other surface or binder mixtures. Use of the stripping inflection points did not prove to be useful in evaluating mixtures.

9.7 Performance of Segregated Mixtures

Examination of the gravel binder mixture shows the very coarse level of segregation results in reduced pavement performance of 16.8 percent due to fatigue and 49 and 73.3 percent due to wheel track testing at 565 and 621 kPa contact pressure, respectively. The coarse level of segregation for the gravel binder mixture shows a reduction of 49.9 percent in performance due to fatigue, but an increase in performance of 65.7 and 48.9 percent in wheel track testing at 565 and 621 kPa contact pressure, respectively.

The gravel surface mixture did not experience failure at all levels of segregation in wheel track testing. However, in fatigue testing the gravel surface mixture did experience reduced performance of 24.1 and 81.6 percent for the coarse and very coarse levels of segregation when compared to the control. The limestone surface and binder mixtures were not fatigue tested, so no conclusions can be drawn for these mixtures with regard to fatigue. Like the gravel surface mixture, not all levels of segregation for the limestone surface and binder mixtures experienced wheel track testing failure.

9.8 Recommendations for Further Study

Areas that warrant further study include theory and application of permittivity, accelerated wheel track testing, design of paving laydown equipment, and implementation of a quality control/quality assurance testing program for segregation measurement. The gradation limits also warrant closer examination.

9.8.1 Non-Destructive Testing Technology

In the area of non-destructive testing, permittivity technology should be pursued. This technology may be able to provide useful information such as volume measurements and type of base pavement . The volume measurements could include the volume of air, asphalt and aggregate. This would enhance detection of segregation. With the recent development of technology, a vector network analyzer may not be needed to assist in the measurement of permittivity. As a result, a more cost-effective device could measure permittivity at predetermined frequencies rather than using a $130,000 vector network analyzer that measures all frequencies.

9.8.2 Laboratory Accelerated Wheel Track Testing

It has been demonstrated that a laboratory wheel test device can be used to effectively evaluate compacted bituminous mixtures in a reasonable period of time. However, sample to sample variation can make it difficult to reach definitive conclusions with respect to wheel track testing. Realizing this, there are two approaches that could be pursued.

The first is to improve sample preparation process. However, the variability of the aggregate may still be significant enough to produce sample to sample variation. The second improvement is to improve wheel track testing boundary conditions. These boundary conditions mainly apply to gross contact pressure. Samples could be tested over a range of gross contact pressures. They could potentially be tested at five different gross contact pressures from 200 kPa up to 2000 kPa. Similar to the fatigue test, the

number of wheel passes to failure verses the contact pressure could be graphically represented. This type of testing would need to be performed on pavements that have a history of both good and poor performance to establish a standard.

9.8.3 Paving Laydown Equipment

Review of Figures 6.14 - 6.18 suggests that transverse segregation is a result of poor operation of the laydown equipment or design flaws in the laydown equipment.

9.8.4 Quality Control/Quality Assurance

In order to initiate an effective quality control/quality assurance (QC/QA) program, the type of density measured in the mixture design and in the field inspection must be the same. Without the two types of density being the same, the field measurement and how to correct it to the design density becomes questionable.

With the introduction of Superpave, the design density is based upon the saturated surface dry density (Asphalt Institute, 1995). However, it has been demonstrated that this technique is inadequate in measuring the true density of field samples that are coarsely segregated. Utilizing the paraffin coating technique may produce more accurate density measurements. However, the field samples could not be extracted to determine the asphalt content. Not obtaining the asphalt content from the same samples as the density would compromise a QC/QA program. This compromise would be especially true if it includes detecting segregation. The binder ignition test might be applicable to determine binder content. However, to date there is no experience in using the National Center for

Asphalt Technology Furnace method for burning off asphalt and paraffin and thus no ignition tests were conducted in this study.

9.8.5 Gradation Limits

The INDOT gradation limits should be examined to determine the impact of the current limits on pavement performance. The coarse level of segregation compared to the control may perform better as a mixture when both fatigue and wheel track testing are considered.

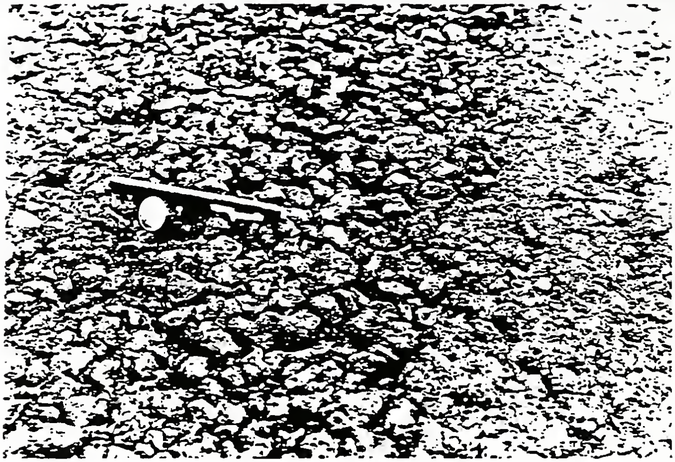

Figure 9.1 Visual Coarse Segregation

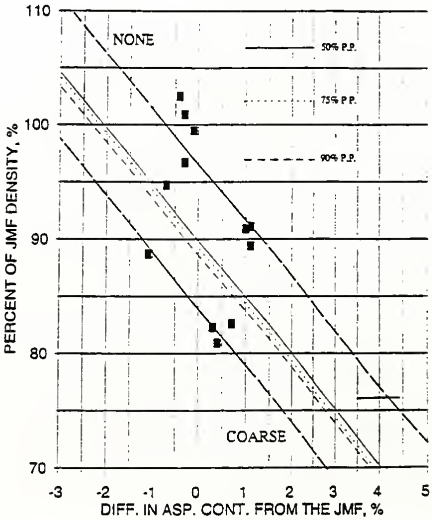

Figure 9.2 Visual Coarse Segregation Classification Based on 4 Minute Nuclear Gauge Readings

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LIST OF REFERENCES

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APPENDICES

APPENDIX A
State of Practice Survey Results

1284 Civil Engineering
Civil Engineering Building Rm. B150
Bituminous Materials Laboratory
Purdue University
West Lafayette, IN 47907-1284

To Whom It May Concern:

I am currently involved in an ongoing research project under Dr. Thomas D. White for the Indiana Department of Transportation (INDOT) Research Division concerning segregation in hot mix asphalt (HMA). I am conducting a survey to determine techniques for prevention of segregation in HMA for the various state agencies across the country. The results of this study will be included in my masters thesis. My thesis involves quantifying segregation and determining a rapid, non-destructive field test to determine the presence of segregation. I am also compiling and producing a video that addresses solutions to common problems in construction and placement of HMA that cause segregation.

Filling out this short questionnaire will be helpful to me and my research. Please take ten minutes to fill this out and return it in the enclosed, stamped envelope. If I have sent this to the wrong person, please forward it to the individual in your agency who could address the matters presented in the survey.

Thank you for your time.

Sincerely,

Gary R Duncan Jr

Gary R. Duncan Jr.
Research Assistant
Purdue University

Questionnaire Concerning DOT Guidelines/Procedures in Prevention of Segregation in HMA.

Gary R Duncan Jr, Research Assistant
Purdue University
16 FEB 94

1. Does your agency have any specifications or guidelines for the prevention of segregation in Hot Mix Asphalt (HMA) during the phases of production and placement?

2. Does your agency train technicians in any trouble-shooting procedures to minimize segregation in the production and placement of quality HMA?

3. Does your agency make any attempts to quantify the degree of segregation (i.e. testing, visual evaluation) when it is known to exist?

4. Does your agency have a reduction in pay factor for stripping? If so, what is the basis for deciding the reduction?

5. Would your agency be interested in training material or presentations concerning procedures to minimize segregation in HMA production and placement?

ALABAMA DOT

Questionnaire Concerning DOT Guidelines/Procedures in Prevention of Segregation in HMA.

Gary R Duncan Jr, Research Assistant
Purdue University
16 FEB 94

1. Does your agency have any specifications or guidelines for the prevention of segregation in Hot Mix Asphalt (HMA) during the phases of production and placement? We have no written specifications or guidelines concerning segregation of HMA.

2. Does your agency train technicians in any trouble-shooting procedures to minimize segregation in the production and placement of quality HMA? Both State & Contractor technicians are trained to minimize segregation in the silo, while loading & unloading haul trucks, and during operation of the paver (particularly, not pulling in the wings) and keeping the hopper at 1/4 full at all times.

3. Does your agency make any attempts to quantify the degree of segregation (i.e. testing, visual evaluation) when it is known to exist? No

4. Does your agency have a reduction in pay factor for stripping? If so, what is the basis for deciding the reduction? There is no pay adjustment, however the paving operation is ceased until the failing stripping is corrected.

5. Would your agency be interested in training material or presentations concerning procedures to minimize segregation in HMA production and placement? Yes

Floyd Strickland
Materials & Tests
AL Dept. of Transportation
3704 Fairground Rd.
Montgomery, AL 36110

ALASKA DOT

Questionnaire Concerning DOT Guidelines/Procedures in Prevention of Segregation in HMA.

Gary R Duncan Jr, Research Assistant
Purdue University
16 FEB 94

1. Does your agency have any specifications or guidelines for the prevention of segregation in Hot Mix Asphalt (HMA) during the phases of production and placement? No. We require the contractor to submit a Paving and Plant Control Plan, part of which includes intended methods for minimizing segregation.

2. Does your agency train technicians in any trouble-shooting procedures to minimize segregation in the production and placement of quality HMA? We have hired consultants to present workshops in the past, but have no ongoing training

3. Does your agency make any attempts to quantify the degree of segregation (i.e. testing, visual evaluation) when it is known to exist? No

4. Does your agency have a reduction in pay factor for stripping? If so, what is the basis for deciding the reduction? NO

5. Would your agency be interested in training material or presentations concerning procedures to minimize segregation in HMA production and placement? Yes

Don Corum

Arizona
602-255-8150

Questionnaire Concerning DOT Guidelines/Procedures in Prevention of Segregation in HMA.

Gary R Duncan Jr, Research Assistant
Purdue University
16 FEB 94

1. Does your agency have any specifications or guidelines for the prevention of segregation in Hot Mix Asphalt (HMA) during the phases of production and placement? To an extent. Plate samples of the in place mix are taken. These samples are tested for extraction and extracted gradation. Pay factors are applied comparing the extracted grading from the mix design targets.

2. Does your agency train technicians in any trouble-shooting procedures to minimize segregation in the production and placement of quality HMA? No

3. Does your agency make any attempts to quantify the degree of segregation (i.e. testing, visual evaluation) when it is known to exist? No

4. Does your agency have a reduction in pay factor for stripping? If so, what is the basis for deciding the reduction? No

5. Would your agency be interested in training material or presentations concerning procedures to minimize segregation in HMA production and placement? Yes

Questionnaire Concerning DOT Guidelines/Procedures in Prevention of Segregation in HMA.

Gary R Duncan Jr, Research Assistant
Purdue University
16 FEB 94

1. Does your agency have any specifications or guidelines for the prevention of segregation in Hot Mix Asphalt (HMA) during the phases of production and placement? Yes - 409.03a(12) attached

2. Does your agency train technicians in any trouble-shooting procedures to minimize segregation in the production and placement of quality HMA?

NO - Touble-shooting is the Contractors' responsibility. Segregation in Arkansas results in removal of the affected area in most cases (see attached specs). In minor instances, a pay adjustment may be made.

3. Does your agency make any attempts to quantify the degree of segregation (i.e. testing, visual evaluation) when it is known to exist?

YES- 410.09a(3) attached

4. Does your agency have a reduction in pay factor for stripping? If so, what is the basis for deciding the reduction?

NO

5. Would your agency be interested in training material or presentations concerning procedures to minimize segregation in HMA production and placement?

NO - However, the Contractor's quality control people may have an interest.

COLORADO

Questionnaire Concerning DOT Guidelines/Procedures in Prevention of Segregation in HMA.

Gary R Duncan Jr, Research Assistant
Purdue University
16 FEB 94

1. Does your agency have any specifications or guidelines for the prevention of segregation in Hot Mix Asphalt (HMA) during the phases of production and placement?

Colorado DOT requires the contractor to document steps he will take to prevent and correct segregation if it occurs during the prepaving conference.

2. Does your agency train technicians in any trouble-shooting procedures to minimize segregation in the production and placement of quality HMA?

CDOT has sponsored training for both CDOT and Contractor personnel at no cost for the last three years (4 sessions of 2 days each) following the "Hot Mix Paving Handbook" (AASHTO, FHWA, etc.) and the increased awareness on the part of both parties has greatly reduced segregation problems on our projects.

We hired J. Scherocman to present training)

3. Does your agency make any attempts to quantify the degree of segregation (i.e. testing, visual evaluation) when it is known to exist?

(See attached DRAFT test method)

This method was seldom tried and never used as a specification. Segregation has to be pretty bad visually before this procedure shows much.

4. Does your agency have a reduction in pay factor for stripping? If so, what is the basis for deciding the reduction?

When project produced hot mix fails the Lottman test, the contractor is required to stop production and correct mix problems prior to restart of paving.

5. Would your agency be interested in training material or presentations concerning procedures to minimize segregation in HMA production and placement?

Yes

CONNECTICUT

Questionnaire Concerning DOT Guidelines/Procedures in Prevention of Segregation in (HMA)

Gary R Duncan Jr, Research Assistant
Purdue University
16 FEB 94

1. Does your agency have any specifications or guidelines for the prevention of segregation in Hot Mix Asphalt (HMA) during the phases of production and placement?

   See copy of specifications attached. Areas that pertain to segregation are high-lighted in red.

2. Does your agency train technicians in any trouble-shooting procedures to minimize segregation in the production and placement of quality HMA?

   YES

3. Does your agency make any attempts to quantify the degree of segregation (i.e. testing, visual evaluation) when it is known to exist?

   Visual evaluation followed by selective sampling and testing; e.g., right and left or front and back of truck to search for variations in grading.

4. Does your agency have a reduction in pay factor for stripping? If so, what is the basis for deciding the reduction?

   NO

5. Would your agency be interested in training material or presentations concerning procedures to minimize segregation in HMA production and placement?

   YES

Questionnaire Concerning DOT Guidelines/Procedures in Prevention of Segregation in HMA.

Gary R Duncan Jr, Research Assistant
Purdue University
16 FEB 94

1. Does your agency have any specifications or guidelines for the prevention of segregation in Hot Mix Asphalt (HMA) during the phases of production and placement?

YES - SPECIFICATIONS

A. AASHTO M-156
B. STANDARD OPERATING PROCEDURES
C. DC STANDARD SPECIFICATIONS 801.05
D. DC STANDARD SPECIFICATIONS 401.07
E. INSPECTORS ARE ASSIGNED TO HMA PLANTS AND PAVING SITES

2. Does your agency train technicians in any trouble-shooting procedures to minimize segregation in the production and placement of quality HMA?

YES

3. Does your agency make any attempts to quantify the degree of segregation (i.e. testing, visual evaluation) when it is known to exist?

NO

4. Does your agency have a reduction in pay factor for stripping? If so, what is the basis for deciding the reduction?

NO

5. Would your agency be interested in training material or presentations concerning procedures to minimize segregation in HMA production and placement?

WE ARE ALWAYS RECEPTIVE TO IMPROVEMENTS IN OUR INSPECTION AND TESTING PROCEDURES

FLORIDA

Questionnaire Concerning DOT Guidelines/Procedures in Prevention of Segregation in HMA.

Gary R Duncan Jr, Research Assistant
Purdue University
16 FEB 94

1. Does your agency have any specifications or guidelines for the prevention of segregation in Hot Mix Asphalt (HMA) during the phases of production and placement?

(Florida Department of Transportation) (FDOT) Specifications prohibit segregation in Hot Mix Asphalt (HMA) but do not include guidelines or methods for prevention during production and placement.

2. Does your agency train technicians in any trouble-shooting procedures to minimize segregation in the production and placement of quality HMA?

Yes, all of the techniques that are known to prevent segregation, from handling of the stockpiles to the paving operations, are taught as part of the Asphalt Plant and Paving Technician Certification courses.

3. Does your agency make any attempts to quantify the degree of segregation (i.e. testing, visual evaluation) when it is known to exist?

Yes, a visual evaluation is made of the texture of each pavement layer. The Contractor is then required to correct any areas having unacceptable texture due to segregation (See attached Specification, Subarticle 330-12.2.)

4. Does your agency have a reduction in pay factor for stripping? If so, what is the basis for deciding the reduction?

No. Stripping has not been a problem in Florida; however, if an excessive amount of stripping were to be detected in a pavement prior to final acceptance it would be removed and replaced.

5. Would your agency be interested in training material or presentations concerning procedures to minimize segregation in HMA production and placement?

Yes, any new material would be appreciated.

GEORGIA

Questionnaire Concerning DOT Guidelines/Procedures in Prevention of Segregation in HMA.

1. Does your agency have any specifications or guidelines for the prevention of segregation in Hot Mix Asphalt (HMA) during the phases of production and placement?

   Yes, a checklist was developed to assist personnel (for both D.O.T. and contractors) in identifying areas where segregation could occur and possible corrective measures. A copy of the checklist is attached.

2. Does your agency train technicians in any trouble-shooting procedures to minimize segregation in the production and placement of quality HMA?

   Yes, we have conducted special workshops at each of our Area Engineers' offices to instruct everyone involved in asphalt construction and inspection what to look for and what to do when segregation is found. We have conducted similar seminars for contractor personnel when asked and have developed two video tapes which address this issue that are available for training.

3. Does your agency make any attempts to quantify the degree of segregation (i.e. testing, visual evaluation) when it is known to exist?

   Yes, a research study conducted for us by Auburn University indicated a 10% deviation from the Job Mix Formula was significant enough that corrective measures were needed. We issued guidelines and then revised our specifications to address this problem based on the Auburn research. A copy of this specification is attached. We have also developed a quick procedure using the nuclear density gauge which can be used to quantify the visual observation, but for corrective work cores are usually taken for extraction and gradation purposes. A copy of a similar investigation and report is attached.

4. Does your agency have a reduction in pay factor for stripping? If so, what is the basis for deciding the reduction?

   No, stripping is not desirable so we would not want to accept it even at a reduced price. We have a tensile strength test procedure (GDT-66) which is used in the mix design procedure to evaluate mixtures susceptible to moisture damage. Mixtures used on state route and interstate construction must have at least 80% retained stability. A boil test (GHD-56) is used at the plant to evaluate the effectiveness of the anti-stripping agent; this is done on a daily basis. If the mixture fails this test, a liquid anti-strip additive may be added in addition to the 1.0% hydrated lime typically used. If the combination still fails, work is suspended until the mixture is evaluated and/or redesigned in the laboratory.

5. Would your agency be interested in training material or presentations concerning procedures to minimize segregation in HMA production and placement?

   Yes, we are always looking for ways to improve our products. Educating and training our personnel to accomplish this objective is a high priority with us.

HAWAII DOT

Questionnaire Concerning DOT Guidelines/Procedures in Prevention of Segregation in HMA.

Gary R Duncan Jr, Research Assistant
Purdue University
16 FEB 94

1. Does your agency have any specifications or guidelines for the prevention of segregation in Hot Mix Asphalt (HMA) during the phases of production and placement? NO

2. Does your agency train technicians in any trouble-shooting procedures to minimize segregation in the production and placement of quality HMA?
ON-THE-JOB-TRAINING

3. Does your agency make any attempts to quantify the degree of segregation (i.e. testing, visual evaluation) when it is known to exist?
VISUAL CHECK

4. Does your agency have a reduction in pay factor for stripping? If so, what is the basis for deciding the reduction? NO

5. Would your agency be interested in training material or presentations concerning procedures to minimize segregation in HMA production and placement? YES

IDAHO DOT

Questionnaire Concerning DOT Guidelines/Procedures in Prevention of Segregation in HMA.

Gary R Duncan Jr, Research Assistant
Purdue University
16 FEB 94

1. Does your agency have any specifications or guidelines for the prevention of segregation in Hot Mix Asphalt (HMA) during the phases of production and placement? The stock piles are constructed by 3' layers + conveyor belt can't drop material more than 6'. Loading the trucks shall be in 3 dumps - The silo hopper has to be 1/3 full or more. The wings of the paver shall only be dumped @ noon or end of day or break down.

2. Does your agency train technicians in any trouble-shooting procedures to minimize segregation in the production and placement of quality HMA? yes each DISTRICT has a training session for the production & placement of plantmix each winter not formally documented

3. Does your agency make any attempts to quantify the degree of segregation (i.e. testing, visual evaluation) when it is known to exist? only by sieve analysis and reject when out of spec

4. Does your agency have a reduction in pay factor for stripping? NO If so, what is the basis for deciding the reduction?

5. Would your agency be interested in training material or presentations concerning procedures to minimize segregation in HMA production and placement? YES

Dwayne H Wiram
Pavement Design Engr
Idaho Transp. Dept
208 334 8450

ILLINOIS DOT

Questionnaire Concerning DOT Guidelines/Procedures in Prevention of Segregation in HMA.

Gary R Duncan Jr, Research Assistant
Purdue University
16 FEB 94

1. Does your agency have any specifications or guidelines for the prevention of segregation in Hot Mix Asphalt (HMA) during the phases of production and placement?

Currently No. However, the Department realizes the problem of segregation and the associated problems which arise due to segregation.

2. Does your agency train technicians in any trouble-shooting procedures to minimize segregation in the production and placement of quality HMA?

The Department, Contractor, and Consultant technicians are informed of proper loading of trucks and paving techniques to further reduce segregation.

3. Does your agency make any attempts to quantify the degree of segregation (i.e. testing, visual evaluation) when it is known to exist?

Currently No. However, the Department is looking at possible segregation specifications, which will demand immediate attention if segregation is encountered.

4. Does your agency have a reduction in pay factor for stripping? If so, what is the basis for deciding the reduction?

No.

5. Would your agency be interested in training material or presentations concerning procedures to minimize segregation in HMA production and placement?

Yes. The Illinois Dept. of Transportation would be very interested in training material or presentations concerning segregation in HMA production and placement in order to prevent this recurring problem.

INDIANA DOT

Questionnaire Concerning DOT Guidelines/Procedures in Prevention of Segregation in HMA.

Gary R Duncan Jr, Research Assistant
Purdue University
16 FEB 94

1. Does your agency have any specifications or guidelines for the prevention of segregation in Hot Mix Asphalt (HMA) during the phases of production and placement? SEE ATTACHED DAILY CHECKLIST.

2. Does your agency train technicians in any trouble-shooting procedures to minimize segregation in the production and placement of quality HMA?
THE DISTRICT BITUMINOUS CONSTRUCTION MANUAL, USED FOR CERTIFICATION OF TECHNICIANS, HAS A SHORT SECTION ON SEGREGATION.

3. Does your agency make any attempts to quantify the degree of segregation (i.e. testing, visual evaluation) when it is known to exist? NO

4. Does your agency have a reduction in pay factor for stripping? If so, what is the basis for deciding the reduction? NO

5. Would your agency be interested in training material or presentations concerning procedures to minimize segregation in HMA production and placement? YES

RON WALKER
BITUMINOUS ENGINEER
INDOT

Questionnaire Concerning DOT Guidelines/Procedures in Prevention of Segregation in HMA.

Gary R Duncan Jr, Research Assistant
Purdue University
16 FEB 94

1. Does your agency have any specifications or guidelines for the prevention of segregation in Hot Mix Asphalt (HMA) during the phases of production and placement? NO

2. Does your agency train technicians in any trouble-shooting procedures to minimize segregation in the production and placement of quality HMA?
YES - THIS WOULD BE COVERED IN PLANT INSPECTION SCHOOLS

3. Does your agency make any attempts to quantify the degree of segregation (i.e. testing, visual evaluation) when it is known to exist?
YES

4. Does your agency have a reduction in pay factor for stripping? If so, what is the basis for deciding the reduction? NO

5. Would your agency be interested in training material or presentations concerning procedures to minimize segregation in HMA production and placement? YES

KANSAS DOT

Questionnaire Concerning DOT Guidelines/Procedures in Prevention of Segregation in HMA.

Gary R Duncan Jr, Research Assistant
Purdue University
16 FEB 94

1. Does your agency have any specifications or guidelines for the prevention of segregation in Hot Mix Asphalt (HMA) during the phases of production and placement? Standard Specifications has requirements for an uniform mat without any segregation. Attached in the 1986 Segregation Seminar information are excerpts from the 1980 Standard Specifications. Our 1990 Standard Specifications contain similar statements. HMA segregation is still a problem. We are developing a specification with a pay factor for density. The draft proposal allows a randomly selected nuclear density location to be moved up to 200' longitudinally to a segregated area. (The nuclear meter will have lower density in the segregated areas.)

2. Does your agency train technicians in any trouble-shooting procedures to minimize segregation in the production and placement of quality HMA?

Yes. The two attachments show some of the information presented in the seminars.

3. Does your agency make any attempts to quantify the degree of segregation (i.e. testing, visual evaluation) when it is known to exist?
Yes. Visually the attached "procedure of Rating Hot Mix Roads for Segregation" is used. Nuclear meter density reading is plotted using the attached graph (See April 9, 1993 letter). Normally, the lowest density and highest amount of segregation occurs 15' to 20' after each paver stop.

4. Does your agency have a reduction in pay factor for stripping? If so, what is the basis for deciding the reduction? No.

5. Would your agency be interested in training material or presentations concerning procedures to minimize segregation in HMA production and placement? Yes, if economical.

Kansas DOT
Rodney Maag, P.E.
Materials and Research
913-296-3711

QUESTIONNAIRE CONCERNING DOT GUIDELINES/PROCEDURES IN PREVENTION OF SEGREGATION IN HMA

ANSWERS

1. Standard Specification Note that for surge / storage systems approved the system cannot segregate or have detrimental effects on the bituminous mixture.

Also, guidelines are specified in the "Bituminous Manual" for causes and prevention of segregation at the hot-mix plant.

Standard Specifications address hauling equipment in regards to causing segregation and Specification's under spreading and finishing require removal and replacement of material that exhibits excessive segregation.

2. When training sessions are conducted, the technicians performing inspection at the hot-mix plant are given guidance in trouble shooting, good practices etc., to minimize segregation.

3. Visual observations are made to determine segregation both in the loaded trucks at the plant site and the in-place mat.

4. A pay factor schedule is not part of the specifications for in place moisture damage / stripping.

5. Yes

Questionaire was completed by Danny Young, Asphalt Field Operations Section, Division of Materials.

Questionnaire Concerning DOT Guidelines/Procedures in Prevention of Segregation in HMA.

Gary R Duncan Jr, Research Assistant
Purdue University
16 FEB 94

From: Jarvis J. Poche, P.E. JJP
Materials Engineer Administrat
Louisiana DOTD
(504) 929-9131

1. Does your agency have any specifications or guidelines for the prevention of segregation in Hot Mix Asphalt (HMA) during the phases of production and placement? Guidelines are presented in a publication entitled "Application of Quality Control Specifications for Asphaltic Concrete Mixtures", available from the Louisiana Transportation Research Center (Phone 504-767-9121).

2. Does your agency train technicians in any trouble-shooting procedures to minimize segregation in the production and placement of quality HMA?

Training is handled by the Louisiana Transportation Research Center.

3. Does your agency make any attempts to quantify the degree of segregation (i.e. testing, visual evaluation) when it is known to exist?

Although patterns of segregation are determined in order to identify potential causes of the problem, no attempt to quantify the degree of segregation is performed.

4. Does your agency have a reduction in pay factor for stripping? If so, what is the basis for deciding the reduction?

No such factor is used.

5. Would your agency be interested in training material or presentations concerning procedures to minimize segregation in HMA production and placement? Yes

Questionnaire Concerning DOT Guidelines/Procedures in Prevention of Segregation in HMA.

Gary R Duncan Jr, Research Assistant
Purdue University
16 FEB 94

1. Does your agency have any specifications or guidelines for the prevention of segregation in Hot Mix Asphalt (HMA) during the phases of production and placement?

Amount of wear on paddles in pugmill.
Length of mixing time.
Don't empty pugmill.
Uniformity of stockpiles.
Flite condition.
We like a batcher on storage silos.

Load Trucks properly.
Keep uniform feed into pave
Maintain uniform level of
in front of screed.
Watch auger at quarter point segregation. (Kick back paddle,

2. Does your agency train technicians in any trouble-shooting procedures to minimize segregation in the production and placement of quality HMA?

yes. Yearly Training. Inspectors are not Certified

3. Does your agency make any attempts to quantify the degree of segregation (i.e. testing, visual evaluation) when it is known to exist?

yes Mostly visual - We will run extractions and cut cores for density.

4. Does your agency have a reduction in pay factor for stripping? If so, what is the basis for deciding the reduction?

No - Not a problem in Maine

5. Would your agency be interested in training material or presentations concerning procedures to minimize segregation in HMA production and placement?

yes

Richard Norton
Maine DOT
Tech Services

MARYLAND

Questionnaire Concerning DOT Guidelines/Procedures in Prevention of Segregation in HMA.

Gary R Duncan Jr, Research Assistant
Purdue University
16 FEB 94

1. Does your agency have any specifications or guidelines for the prevention of segregation in Hot Mix Asphalt (HMA) during the phases of production and placement? YES

2. Does your agency train technicians in any trouble-shooting procedures to minimize segregation in the production and placement of quality HMA?

YES, WE STARTED TRAINING OFFERED BY NAPA ON "HOT MIX ASPHALT CONSTRUCTION." AS A PART OF THIS COURSE THEY TEACH ABOUT TROUBLE-SHOOTING PROCEDURES AND MINIMIZING/AVOIDING SEGREGATION.

3. Does your agency make any attempts to quantify the degree of segregation (i.e. testing, visual evaluation) when it is known to exist?

NO

4. Does your agency have a reduction in pay factor for stripping? If so, what is the basis for deciding the reduction?

NO, HOWEVER, OUR MIX DESIGN PROCEDURE REQUIRES TO TEST FOR STRIPPING PRIOR TO THE APPROVAL OF MIX DESIGN. WE REQUIRE A MINIMUM TSR OF 0.85 USING D4867 (FREEZE/THAW CYCLE REQUIRED).

5. Would your agency be interested in training material or presentations concerning procedures to minimize segregation in HMA production and placement?

YES

MICHIGAN

Questionnaire Concerning DOT Guidelines/Procedures in Prevention of Segregation in HMA.

Gary R Duncan Jr, Research Assistant
Purdue University
16 FEB 94

1. Does your agency have any specifications or guidelines for the prevention of segregation in Hot Mix Asphalt (HMA) during the phases of production and placement? Only that it is not allowed. Reverse paddles are ~~not~~ required ~~allowed~~ but this is more to insure uniform compaction under the screed.

2. Does your agency train technicians in any trouble-shooting procedures to minimize segregation in the production and placement of quality HMA? Only in the placement. This training is in the area of material through the paver hopper, adjustment of screed and augers.

3. Does your agency make any attempts to quantify the degree of segregation (i.e. testing, visual evaluation) when it is known to exist?

No –

4. Does your agency have a reduction in pay factor for stripping? If so, what is the basis for deciding the reduction? No

5. Would your agency be interested in training material or presentations concerning procedures to minimize segregation in HMA production and placement? Yes.

MINNESOTA DOT

Questionnaire Concerning DOT Guidelines/Procedures in Prevention of Segregation in HMA.

Gary R Duncan Jr, Research Assistant
Purdue University
16 FEB 94

1. Does your agency have any specifications or guidelines for the prevention of segregation in Hot Mix Asphalt (HMA) during the phases of production and placement? No, Specifications state segregation is not acceptable but no methods to prevent it are defined. Visual checks for segregation are done as mix is loaded into trucks and on the street.

2. Does your agency train technicians in any trouble-shooting procedures to minimize segregation in the production and placement of quality HMA?
No. Segregation is discussed in Bituminous Certification Classes but no formal training regarding trouble-shooting is discussed.

3. Does your agency make any attempts to quantify the degree of segregation (i.e. testing, visual evaluation) when it is known to exist?
yes Opent ten areas, may be subject to a price reduction (Visual Inspection)

4. Does your agency have a reduction in pay factor for stripping? If so, what is the basis for deciding the reduction?
No; Although other mix parameters must meet specifications. Pay reductions may be assessed for low AC content, failing gradations, and aggregate quality

5. Would your agency be interested in training material or presentations concerning procedures to minimize segregation in HMA production and placement? yes. when available please contact,

DAN Wegman
Bituminous Engineer - MN DOT
1400 Gervais Ave
Maplewood, Mn 55109

MISSISSIPPI

Questionnaire Concerning DOT Guidelines/Procedures in Prevention of Segregation in HMA.

Gary R Duncan Jr, Research Assistant
Purdue University
16 FEB 94

1. Does your agency have any specifications or guidelines for the prevention of segregation in Hot Mix Asphalt (HMA) during the phases of production and placement? NO

2. Does your agency train technicians in any trouble-shooting procedures to minimize segregation in the production and placement of quality HMA? NO

3. Does your agency make any attempts to quantify the degree of segregation (i.e. testing, visual evaluation) when it is known to exist? NO

4. Does your agency have a reduction in pay factor for stripping? If so, what is the basis for deciding the reduction? NO

5. Would your agency be interested in training material or presentations concerning procedures to minimize segregation in HMA production and placement? YES

MISSOURI DOT
JEFFERSON CITY, MO

Questionnaire Concerning DOT Guidelines/Procedures in Prevention of Segregation in HMA.

Gary R Duncan Jr, Research Assistant
Purdue University
16 FEB 94

1. Does your agency have any specifications or guidelines for the prevention of segregation in Hot Mix Asphalt (HMA) during the phases of production and placement?

See attached specification excerpts.

2. Does your agency train technicians in any trouble-shooting procedures to minimize segregation in the production and placement of quality HMA?

See attached Appendix E.

3. Does your agency make any attempts to quantify the degree of segregation (i.e. testing, visual evaluation) when it is known to exist?

See attached Appendix E.

4. Does your agency have a reduction in pay factor for stripping? If so, what is the basis for deciding the reduction?

No.

5. Would your agency be interested in training material or presentations concerning procedures to minimize segregation in HMA production and placement?

Yes.

Questionnaire Concerning DOT Guidelines/Procedures in Prevention of Segregation in HMA.

Gary R Duncan Jr, Research Assistant
Purdue University
16 FEB 94

1. Does your agency have any specifications or guidelines for the prevention of segregation in Hot Mix Asphalt (HMA) during the phases of production and placement? Yep.

2. Does your agency train technicians in any trouble-shooting procedures to minimize segregation in the production and placement of quality HMA? Yep.

3. Does your agency make any attempts to quantify the degree of segregation (i.e. testing, visual evaluation) when it is known to exist? Yep.

stripping - No.
Segregation - yes

4. Does your agency have a reduction in pay factor for ~~stripping~~ Segregation? If so, what is the basis for deciding the reduction? Segregation: nuclear density Seg. area and then smear a Cement slurry in to voids Region, Retest for Nuke density ∴ if slurried density is greater than the original density by 6 pounds then its Segregated. - Removal of a[illegible]   See Att[illegible]

5. Would your agency be interested in training material or presentations concerning procedures to minimize segregation in HMA production and placement? Yep

NEBRASKA

Questionnaire Concerning DOT Guidelines/Procedures in Prevention of Segregation in HMA.

Gary R Duncan Jr, Research Assistant
Purdue University
16 FEB 94

1. Does your agency have any specifications or guidelines for the prevention of segregation in Hot Mix Asphalt (HMA) during the phases of production and placement? Not specifically. We are going away from large aggregates (> 3/4") in our mixes, which will reduce our segregation problems.

2. Does your agency train technicians in any trouble-shooting procedures to minimize segregation in the production and placement of quality HMA?

yes

3. Does your agency make any attempts to quantify the degree of segregation (i.e. testing, visual evaluation) when it is known to exist?

yes

4. Does your agency have a reduction in pay factor for stripping? If so, what is the basis for deciding the reduction?

No

5. Would your agency be interested in training material or presentations concerning procedures to minimize segregation in HMA production and placement? yes

NEW HAMPSHIRE

Questionnaire Concerning DOT Guidelines/Procedures in Prevention of Segregation in HMA.

Gary R Duncan Jr, Research Assistant
Purdue University
16 FEB 94

1. Does your agency have any specifications or guidelines for the prevention of segregation in Hot Mix Asphalt (HMA) during the phases of production and placement? No

2. Does your agency train technicians in any trouble-shooting procedures to minimize segregation in the production and placement of quality HMA? No

3. Does your agency make any attempts to quantify the degree of segregation (i.e. testing, visual evaluation) when it is known to exist? Visually

4. Does your agency have a reduction in pay factor for stripping? If so, what is the basis for deciding the reduction? No

5. Would your agency be interested in training material or presentations concerning procedures to minimize segregation in HMA production and placement? Yes

NJ DOT

Questionnaire Concerning DOT Guidelines/Procedures in Prevention of Segregation in HMA.

Gary R Duncan Jr, Research Assistant
Purdue University
16 FEB 94

1. Does your agency have any specifications or guidelines for the prevention of segregation in Hot Mix Asphalt (HMA) during the phases of production and placement? No. Segregated material may be rejected under a general provision which allows the Engineer to reject material which is "contaminated, segregated, improper temperature or improperly coated".

2. Does your agency train technicians in any trouble-shooting procedures to minimize segregation in the production and placement of quality HMA?
In Asphalt Plant Technician and Asphalt Paving Technician training courses, segregation is one of the topics addressed.

3. Does your agency make any attempts to quantify the degree of segregation (i.e. testing, visual evaluation) when it is known to exist?

No.

4. Does your agency have a reduction in pay factor for stripping? If so, what is the basis for deciding the reduction? No. Stripping is not a major problem in New Jersey.

5. Would your agency be interested in training material or presentations concerning procedures to minimize segregation in HMA production and placement?

Yes.

Questionnaire Concerning DOT Guidelines/Procedures in Prevention of Segregation in HMA.

Gary R Duncan Jr, Research Assistant
Purdue University
16 FEB 94

1. Does your agency have any specifications or guidelines for the prevention of segregation in Hot Mix Asphalt (HMA) during the phases of production and placement? A GENERAL STATEMENT THAT SEGREGATED MATERIAL WILL BE REMOVED AND REPLACED WITH ACCEPTABLE MIX.

2. Does your agency train technicians in any trouble-shooting procedures to minimize segregation in the production and placement of quality HMA?

YES.

3. Does your agency make any attempts to quantify the degree of segregation (i.e. testing, visual evaluation) when it is known to exist? NO

4. Does your agency have a reduction in pay factor for stripping? If so, what is the basis for deciding the reduction? NO STRIPPING IS CONTROLLED BY USING HYDRATED LIME IN THE MIX. THERE IS A PAY FACTOR FOR LIME CONTENT.

5. Would your agency be interested in training material or presentations concerning procedures to minimize segregation in HMA production and placement? YES.

JIM STOKES
NEW MEXICO DOT
(505) 827-5541

NEW YORK

Questionnaire Concerning DOT Guidelines/Procedures in Prevention of Segregation in HMA.

Gary R Duncan Jr, Research Assistant
Purdue University
16 FEB 94

1. Does your agency have any specifications or guidelines for the prevention of segregation in Hot Mix Asphalt (HMA) during the phases of production and placement? Yes. Attached are specifications which pertain to the mixer unit and the Hot Bituminous Mixer Holding Bin. The producer is not required to own a holding bin.

2. Does your agency train technicians in any trouble-shooting procedures to minimize segregation in the production and placement of quality HMA?

No. Only to be aware it can happen and reject the mixture if it does happen. The rejection is supported by the fact the mixture does not meet gradation specification requirements.

3. Does your agency make any attempts to quantify the degree of segregation (i.e. testing, visual evaluation) when it is known to exist?

Yes Through gradation testing.

4. Does your agency have a reduction in pay factor for stripping? If so, what is the basis for deciding the reduction?

No. If stripping is detected, anti-stripping additive may be required.

5. Would your agency be interested in training material or presentations concerning procedures to minimize segregation in HMA production and placement?

Segregation has not been a problem in producing and placing of HMA in the state. Would be interested in training material for minimizing segregation.

NORTH CAROLINA DOT

Questionnaire Concerning DOT Guidelines/Procedures in Prevention of Segregation in HMA.

Gary R Duncan Jr, Research Assistant
Purdue University
16 FEB 94

1. Does your agency have any specifications or guidelines for the prevention of segregation in Hot Mix Asphalt (HMA) during the phases of production and placement? General Statements. but nothing definitive.

2. Does your agency train technicians in any trouble-shooting procedures to minimize segregation in the production and placement of quality HMA?

Yes - emphasize good construction techniques thru all phases of production & laydown

3. Does your agency make any attempts to quantify the degree of segregation (i.e. testing, visual evaluation) when it is known to exist?

No

4. Does your agency have a reduction in pay factor for stripping? If so, what is the basis for deciding the reduction?

No

5. Would your agency be interested in training material or presentations concerning procedures to minimize segregation in HMA production and placement?

Yes -

Questionnaire Concerning DOT Guidelines/Procedures in Prevention of Segregation in HMA.

Gary R Duncan Jr, Research Assistant
Purdue University
16 FEB 94

1. Does your agency have any specifications or guidelines for the prevention of segregation in Hot Mix Asphalt (HMA) during the phases of production and placement?

We randomly sample HMA but if an area is considered segregated we sample that area and have the right to remove it. Stock piles are split in at least 2 Fractions.

2. Does your agency train technicians in any trouble-shooting procedures to minimize segregation in the production and placement of quality HMA?

QC/QA training for technicians involves visual determination of segregation.

3. Does your agency make any attempts to quantify the degree of segregation (i.e. testing, visual evaluation) when it is known to exist?

If HMA is determined, by visual inspection, to be segregated we test that area. Large Stone mix is given a definition for Segregation by plan note.

4. Does your agency have a reduction in pay factor for stripping? If so, what is the basis for deciding the reduction?

Stripping has not been a major problem.

5. Would your agency be interested in training material or presentations concerning procedures to minimize segregation in HMA production and placement?

Segregation has not been a big problem.

OHIO DOT

Questionnaire Concerning DOT Guidelines/Procedures in Prevention of Segregation in HMA.

Gary R Duncan Jr, Research Assistant
Purdue University
16 FEB 94

1. Does your agency have any specifications or guidelines for the prevention of segregation in Hot Mix Asphalt (HMA) during the phases of production and placement? Only visual as placed or visual in truck load

2. Does your agency train technicians in any trouble-shooting procedures to minimize segregation in the production and placement of quality HMA? Contractor and ODOT personnel receive various forms of training. Primarily seminars, of which segregation is discussed

3. Does your agency make any attempts to quantify the degree of segregation (i.e. testing, visual evaluation) when it is known to exist? quantify degree? - no

4. Does your agency have a reduction in pay factor for stripping? If so, what is the basis for deciding the reduction? No

5. Would your agency be interested in training material or presentations concerning procedures to minimize segregation in HMA production and placement? No, we are already aware of its various causes and have attempted to address thru design spec's less prone to segregation.

Questionnaire Concerning DOT Guidelines/Procedures in Prevention of Segregation in HMA.

Gary R Duncan Jr, Research Assistant
Purdue University
16 FEB 94

1. Does your agency have any specifications or guidelines for the prevention of segregation in Hot Mix Asphalt (HMA) during the phases of production and placement? Specification states
"Segregation of the mixture will not be acceptable."

2. Does your agency train technicians in any trouble-shooting procedures to minimize segregation in the production and placement of quality HMA?
yes in ongoing classes

3. Does your agency make any attempts to quantify the degree of segregation (i.e. testing, visual evaluation) when it is known to exist?
visual evaluation

4. Does your agency have a reduction in pay factor for stripping? If so, what is the basis for deciding the reduction? NO
we do have a stripping test similar to AASHTO T-283 used to determine stripping problems.

5. Would your agency be interested in training material or presentations concerning procedures to minimize segregation in HMA production and placement? Possibly

OREGON DEPT OF TRANSPOR

Questionnaire Concerning DOT Guidelines/Procedures in Prevention of Segregation in HMA.

Gary R Duncan Jr, Research Assistant
Purdue University
16 FEB 94

1. Does your agency have any specifications or guidelines for the prevention of segregation in Hot Mix Asphalt (HMA) during the phases of production and placement? Yes - Oregon's specifications address segregation during storage, loading of trucks and when depositing during paving operations.

2. Does your agency train technicians in any trouble-shooting procedures to minimize segregation in the production and placement of quality HMA?

Yes - NHI Course on HMA Construction

3. Does your agency make any attempts to quantify the degree of segregation (i.e. testing, visual evaluation) when it is known to exist?

No

4. Does your agency have a reduction in pay factor for stripping? If so, what is the basis for deciding the reduction? No.

5. Would your agency be interested in training material or presentations concerning procedures to minimize segregation in HMA production and placement? Yes

PENN. DOT

Questionnaire Concerning DOT Guidelines/Procedures in Prevention of Segregation in HMA.

Gary R Duncan Jr, Research Assistant
Purdue University
16 FEB 94

1. Does your agency have any specifications or guidelines for the prevention of segregation in Hot Mix Asphalt (HMA) during the phases of production and placement? No

2. Does your agency train technicians in any trouble-shooting procedures to minimize segregation in the production and placement of quality HMA?
Recently we ~~have~~ held regional 1-Day workshops, jointly with the Asphalt Institute's and the State's Paving Assoc. addressing basics required for Quality pavements. (Segregation was a topic). Although this program is not routine currently, we would like to continue on some frequency - such as annually.

3. Does your agency make any attempts to quantify the degree of segregation (i.e. testing, visual evaluation) when it is known to exist? Visual is only adequate when segregation is extreme. Currently, we are attempting to quantify on less obvious cases by Coring & measuring Density & Mix Composition and comparing to specification requires.

4. Does your agency have a reduction in pay factor for stripping? If so, what is the basis for deciding the reduction? We take random loose mix samples and cores of compacted pavement, from behind the paver. Pay factors are Asphalt Content, - #200 matl. & Density relative to Rice specific gravity.

5. Would your agency be interested in training material or presentations concerning procedures to minimize segregation in HMA production and placement? I believe we have adequate material concerning controlling or minimizing. However, anything new in the concept of identifying in rapid and easy way would be of interest.

(over)

RHODE ISLAND DEPARTMENT OF TRANSPORTATION
DIVISION OF PUBLIC WORKS
MATERIAL SECTION
2 CAPITOL HILL
PROVIDENCE, RHODE ISLAND 02903

RHODE ISLAND DOT

Questionnaire Concerning DOT Guidelines/Procedures in Prevention of Segregation in HMA.

Gary R Duncan Jr, Research Assistant
Purdue University
16 FEB 94

1. Does your agency have any specifications or guidelines for the prevention of segregation in Hot Mix Asphalt (HMA) during the phases of production and placement? Stockpiles are maintained following standard industry practices to minimize segregation.

2. Does your agency train technicians in any trouble-shooting procedures to minimize segregation in the production and placement of quality HMA?
They are taught to recognize segregation in stockpiles.

3. Does your agency make any attempts to quantify the degree of segregation (i.e. testing, visual evaluation) when it is known to exist?
A sieve analysis will be performed if segregation is known to exist.

4. Does your agency have a reduction in pay factor for stripping? If so, what is the basis for deciding the reduction? No.

5. Would your agency be interested in training material or presentations concerning procedures to minimize segregation in HMA production and placement? Yes.

Questionnaire Concerning DOT Guidelines/Procedures in Prevention of Segregation in HMA.

Gary R Duncan Jr, Research Assistant
Purdue University
16 FEB 94

1. Does your agency have any specifications or guidelines for the prevention of segregation in Hot Mix Asphalt (HMA) during the phases of production and placement?

Our Department has inspector training schools with manuals that discuss construction practices for minimizing segregation.

2. Does your agency train technicians in any trouble-shooting procedures to minimize segregation in the production and placement of quality HMA?

Our Department has asphalt plant and road inspector schools which discuss the prevention of segregation.

3. Does your agency make any attempts to quantify the degree of segregation (i.e. testing, visual evaluation) when it is known to exist?

The finished mat is visually inspected for segregation. Severely segregated sections are removed and replaced. There are no formal attempts to actually quantify (measure).

4. Does your agency have a reduction in pay factor for stripping? If so, what is the basis for deciding the reduction?

Sections of roadway that are ravelled out by traffic during construction are usually removed and replaced by the Contractor at his expense.

5. Would your agency be interested in training material or presentations concerning procedures to minimize segregation in HMA production and placement?

We would be interested in training materials for our schools.

SOUTH DAKOTA

Questionnaire Concerning DOT Guidelines/Procedures in Prevention of Segregation in HMA.

Gary R Duncan Jr, Research Assistant
Purdue University
16 FEB 94

1. Does your agency have any specifications or guidelines for the prevention of segregation in Hot Mix Asphalt (HMA) during the phases of production and placement? The S.D. D.O.T. Specifies paver feeders or pick-up machines for mixes 3/4" or larger.

2. Does your agency train technicians in any trouble-shooting procedures to minimize segregation in the production and placement of quality HMA? Briefly, during general asphalt Training progr

3. Does your agency make any attempts to quantify the degree of segregation (i.e. testing, visual evaluation) when it is known to exist? Engineering judgement on a case by case basis.

4. Does your agency have a reduction in pay factor for stripping? If so, what is the basis for deciding the reduction? No. Generally require repair.

5. Would your agency be interested in training material or presentations concerning procedures to minimize segregation in HMA production and placement? No. We have had limited problems to date.

Questionnaire Concerning DOT Guidelines/Procedures in Prevention of Segregation in HMA.

Gary R Duncan Jr, Research Assistant
Purdue University
16 FEB 94

1. Does your agency have any specifications or guidelines for the prevention of segregation in Hot Mix Asphalt (HMA) during the phases of production and placement? We have no special provisions. We state that when segregation is detected, ~~it should be~~ ~~cor~~ Action should be taken to stop it.

2. Does your agency train technicians in any trouble-shooting procedures to minimize segregation in the production and placement of quality HMA? Yes, in Construction Inspection Training.

3. Does your agency make any attempts to quantify the degree of segregation (i.e. testing, visual evaluation) when it is known to exist? NO

4. Does your agency have a reduction in pay factor for stripping? If so, what is the basis for deciding the reduction? No

5. Would your agency be interested in training material or presentations concerning procedures to minimize segregation in HMA production and placement? Yes

UTAH

Questionnaire Concerning DOT Guidelines/Procedures in Prevention of Segregation in HMA.

Gary R Duncan Jr, Research Assistant
Purdue University
16 FEB 94

1. Does your agency have any specifications or guidelines for the prevention of segregation in Hot Mix Asphalt (HMA) during the phases of production and placement? — no, not spelled out.

2. Does your agency train technicians in any trouble-shooting procedures to minimize segregation in the production and placement of quality HMA? — Some, but not at the level it should be.

3. Does your agency make any attempts to quantify the degree of segregation (i.e. testing, visual evaluation) when it is known to exist? -
testing - no
visual - yes, but not quantify

4. Does your agency have a reduction in pay factor for stripping? If so, what is the basis for deciding the reduction? — no

5. Would your agency be interested in training material or presentations concerning procedures to minimize segregation in HMA production and placement? — yes.

VIRGINIA DOT

Questionnaire Concerning DOT Guidelines/Procedures in Prevention of Segregation in HMA.

Gary R Duncan Jr, Research Assistant
Purdue University
16 FEB 94

Bob Horan
Virginia DOT
Asst. State Materials Engr.
804 328.3106

1. Does your agency have any specifications or guidelines for the prevention of segregation in Hot Mix Asphalt (HMA) during the phases of production and placement? No. Specifications state that compacted roadway must be uniform and smooth.

2. Does your agency train technicians in any trouble-shooting procedures to minimize segregation in the production and placement of quality HMA?

Yes. In the asphalt paving school (Materials Certification schools) there is a section concerning the causes and cures of segregation. This includes some diagnostic charts to assist in identifying the cause

3. Does your agency make any attempts to quantify the degree of segregation (i.e. testing, visual evaluation) when it is known to exist?

No

4. Does your agency have a reduction in pay factor for stripping? If so, what is the basis for deciding the reduction? No

5. Would your agency be interested in training material or presentations concerning procedures to minimize segregation in HMA production and placement? Yes

West Virg

Questionnaire Concerning DOT Guidelines/Procedures in Prevention of Segregation in HMA.

Gary R Duncan Jr, Research Assistant
Purdue University
16 FEB 94

1. Does your agency have any specifications or guidelines for the prevention of segregation in Hot Mix Asphalt (HMA) during the phases of production and placement?

Yes. Our specifications have several references throughoot the production and placement sections referring to prevention of segregation.

2. Does your agency train technicians in any trouble-shooting procedures to minimize segregation in the production and placement of quality HMA?

Yes. We cover certain areas of segregation in our Certified HMA Technician School.

3. Does your agency make any attempts to quantify the degree of segregation (i.e. testing, visual evaluation) when it is known to exist?

Usually by visual evaluation. Sometimes by gradation analysis.

4. Does your agency have a reduction in pay factor for stripping? If so, what is the basis for deciding the reduction?

No.

5. Would your agency be interested in training material or presentations concerning procedures to minimize segregation in HMA production and placement?

We have some training material, but we may be interested in additional material.

Questionnaire Concerning DOT Guidelines/Procedures in Prevention of Segregation in HMA.

Gary R Duncan Jr, Research Assistant
Purdue University
16 FEB 94

1. Does your agency have any specifications or guidelines for the prevention of segregation in Hot Mix Asphalt (HMA) during the phases of production and placement?

Yes, the specification states any load or loads of mixture which, in the opinion of the Engineer, are unacceptable for reason of being excessively segregated, aggregates improperly coated, or of excessively high or low temperature shall be rejected for use in the work.

2. Does your agency train technicians in any trouble-shooting procedures to minimize segregation in the production and placement of quality HMA?

Yes, we have a Roadway Inspector's Certification program and a Plant Inspector's Certification program.

3. Does your agency make any attempts to quantify the degree of segregation (i.e. testing, visual evaluation) when it is known to exist?

Yes, segregation produces a non-uniform mix. Therefore, to quantify the degree of segregation, core samples of the mix are obtained at three locations transversley across the pavement for a gradation determination.

4. Does your agency have a reduction in pay factor for stripping? If so, what is the basis for deciding the reduction?

No.

5. Would your agency be interested in training material or presentations concerning procedures to minimize segregation in HMA production and placement?

Possibly.

APPENDIX B

Training Video Script

Properly designed, produced and placed Hot Mix Asphalt provides durable, long lasting pavements, requiring little maintenance. Yet segregation of these mixtures has caused problems in the paving industry. Problems that can be avoided.
Segregation is a process which results in a non-uniform aggregate stockpile, gradation or HMA mix that contains concentrated areas of fine and coarse aggregate. Segregated HMA mixes do not perform the way they are designed.
Fine areas of the segregated HMA hold the majority of the asphalt in the mix, which makes them over rich with asphalt, have low air voids and a tendency to rut and shove. Coarse areas of a segregated HMA are deficient in asphalt and lack the fine mastic to hold the larger, coarse aggregate in place, which may lead to ravelling. Coarse areas are also more permeable, allowing water to enter the pavement which could cause stripping of the mat.
We are going to show you the five steps of the HMA production and construction processes where segregation can occur. They are.......mix design......production and stockpiling of aggregate......HMA manufacturing and storage facilities.......truck loading and transfer......and paving.

Segregation can be reduced considerably by properly designing the mix. Mixes that are well designed tend to be more forgiving and allow for mistakes in HMA construction. Gap graded mixes should be avoided since they are unforgiving and at low asphalt contents usually can not be produced without segregation, regardless of the equipment or techniques used.
The maximum density curve can be a guide to ensure proper mix design. A gradation that falls directly on the maximum density curve should not be used since it would leave insufficient room for the asphalt. The designer should select two to four percentage points above the curve for a finer texture. For a coarser texture, select two to four percentage points below the curve. A grading curve that roughly parallels the maximum density line will produce uniformly graded mixes that are more forgiving. However, the maximum density curve should only be used as a guide for mix design and density. Other criteria, such as air voids, VMA and stability are also important.

Proper stockpiling techniques will help ensure that uniform materials are being supplied to the HMA manufacturing facility. In a conical stockpile .... segregation will occur because the larger stones tend to roll down the sides and to the outside of the pile. If this occurs, segregated materials will be fed to the mix plant unless they are remixed beforehand.
When constructing stockpiles with trucks, the aggregate should be piled in units not larger than a single truckload and no higher than one layer of truckloads.
When using a crane or a bucket, the loads should be deposited adjacent to and overlapping one another to form a layer of uniform thickness.
Stockpiles should be built in progressive, horizontal layers.
When a conveyor is used, a bulldozer should be used to distribute the pile in horizontal layers to keep the aggregate from forming a conical pile.

Do not build stockpiles by dropping material from a high conveyor. The conveyor should be low enough to prevent the wind from blowing the fines away from the coarse fraction as it drops.
If the stockpile is constructed on a slope using a bulldozer, it should be built in progressive layers not greater than a 3 to 1 slope, with no aggregate dumped down the backside of the pile.
The use of dozers should be kept to a minimum, especially in cases where the aggregate supporting the weight of the dozer is friable and susceptible to crushing and packing.
If dozers are used, they should not be allowed to work continuously in the same trough on each layer. If they work too long in the same trough, the dozer may crush the material, producing fines and causing a non-uniform area in each layer of the stockpile.
These are problems not only with dozers, but all tracked vehicles and rubber tired equipment.

Segregation can occur at several points in an HMA manufacturing facility, depending on whether it is a Batch mixing facility, or a Drum mixing facility. Generally, the problems develop in Cold Feed Bins, in both batch and drum dryer facilities....in Hot Bins in batch plants......in drum mixers and in surge bins.
In cold feed bins, segregation does not usually occur unless blended aggregates consisting of varied sizes are fed into the facility. Segregation should not occur when a single-sized aggregate is placed in a feed bin.
When segregation is found to be occurring in the feed bins, there is a problem either in the stockpiling technique or there is some bridging of material causing non-uniformity of feeding from the bin itself.
An improved bin opening that allows for a self-relieving bottom will provide a uniform feed all along the opening of the cold feed bin.
In drum mixer facilities, segregation must be prevented before the aggregate enters the drum. It must be eliminated in the stockpiles or the cold feed bins since the material will not be separated out again through the screens as in a batch plant.
In batch plants, hot bins are used to temporarily store the heated aggregate after it has been sent through the screens. Each bin is an individual compartment which holds differing size aggregates before being discharged into a weigh hopper.
There are generally three hot bins. Hot bin number 1 holds fine material....hot bin number 2 holds intermediate size material....and hot bin number 3 holds the coarse material.
Segregation can occur with all sizes of materials in the number one hot bin due to the size and shape of the bin and the wide range of material sizes placed in it. The main concern of the number one hot bin is the return of dust from the baghouse. It generally collects toward the front of the bin and lies there until the bin is almost empty. It then breaks loose and surges into the weigh hopper as a segregated, ultrafine mix.
An inexpensive solution to the problem is to install a baffle that forces the dust to fall in the center of the bin, where it can be uniformly mixed with the slightly coarser material in the bin.
Another solution is to maintain the level within the bin at a high enough point where the

dust will not fall out in large surges.
There are no hot bins in a drum dryer, so this is not a concern for those plants.

There are several configurations of drum mixing facilities.....the single drum...the dual drum in series.....and the double drum. We'll focus on the single drum mixer since there is limited research available on segregation in the other configurations.
Segregation can be a problem in drum mixers and there are varied causes and solutions. Segregation can be reduced by achieving better asphalt coating. Extending the asphalt line farther into the drum will increase mixing time. Kick back flights can be used to push the aggregate back into the mixing area for increased mixing time. However, the addition of kick back flights or dams, or decreasing the drum slope could decrease the production capacity of the plant due to increased drum loads. Adding dams, or decreasing the drum slope would increase the mixing time.
Drum discharge can also cause segregation if proper precautions are not taken. Gravity discharge of drum material is very sensitive to segregation. When the material is discharged, coarse material tends to separate itself from the fine material and will be segregated as it goes onto the drag conveyor and into the surge bin. There are ways to alleviate the problem. Restricting the discharge chute from the drum will force the discharge into the center of the conveyor. Install a plow or single discharge point in the drum. Or, set the drag conveyor at a 90 degree angle to the drum discharge to force a right angle change in material flow, which would essentially mix the segregated material.

Segregation can also occur on the drag conveyors. A drag conveyor is a conveyor belt equipped with flights to carry the HMA to the storage silo or surge bin. Segregation can occur on the drag conveyor when fine material builds up on the bottom of each flight and coarse material falls backwards down the drag conveyor. This process is sometimes referred to as hydroplaning. Segregation on a drag conveyor can be significant when the plant operation is started and stopped. Drag conveyors should be equipped with floating hold downs and heated bottoms for cold start-ups to minimize this source of segregation.

The surge bins, or storage silos, are necessary for temporary storage of HMA in all types of plants and for controlled truck loading in drum mixer facilities. The large size of these silos, both in diameter and height, contribute to segregation problems. Researchers have found two devices that help eliminate segregation in this sensitive area....a bin loading batcher at the top of the bin.....and a rotating chute at the top of the bin.
When using rotating chutes, it is essential that the material be directed downward. If the end of the chute wears out, material is thrown to the outside wall of the bin. The coarse material will be forced back to the center of the bin but the fines will stick to the wall, causing the mix to segregate.
The silo batcher is perhaps the most popular device for eliminating segregation in the surge silos. There are several ways to reduce or eliminate segregation with silo batchers. The batcher should hold at least two tons and have a large diameter gate opening to ensure complete and rapid discharge.
The batcher should be filled completely each time to obtain an adequate volume of

material for integrity of the batch when it is dropped. Timers should not be used on the batchers.
The batcher should not be completely emptied each drop. This will reduce random segregation.
Segregation in the storage silo is sensitive to the height of the material maintained in the silo. If the height of the material in the silo is too low (falling below the top of the bottom cone) then the coarse material will separate as the HMA is emptied, causing segregation. If the silo is kept too full, then the mix falling into the silo will tend to form a conical pile which contributes to separation of the coarse and fine fraction of the mix.

Rapid truck loading is a major cause of segregation. Trucks should be loaded with distributed batches. If not, the coarse material will collect on the outside walls of the truck and be the first and last material to be loaded into the paver, causing areas of segregation in the pavement between truck loads.
If a weigh batcher is used, the material is batched into the truck similar to the silo batcher and segregation can be considerably reduced. Using a weigh batcher will help ensure a uniform transfer of material into the truck.
If the truck is loaded in three separate drops, as shown here, coarse material will roll to the middle of the truck and be covered by the successive drops. This loading will promote a uniform discharge into the paver.
Another source of segregation occurs during hauling of the mix by truck to the jobsite. If the haul distance is long, or over rough roads, the stiff ride of the truck may shake the mixture considerably and cause segregation. It is recommended that haul distances be as short as possible and over the best roads available.
Even if the recommendations presented up to this point are followed, segregation can still occur in the HMA paving machine. There are guidelines to follow to ensure that segregation does not occur in the paving process.
Do not completely empty the hopper between truck loads. Coarse material tends to roll into the wings of the hopper when HMA is unloaded from the truck. If the hopper is not empty, the material will be uniformly fed to the drag flights since it will not be able to collect in the hopper wings.
Do not completely dump the hopper wings between loads.
Ensure that the truck operators dump the full truckload of HMA to flood the hopper. When the hopper is full, the material tends to be conveyed out from under the truck and does not roll and segregate as it is dumped.
Open the hopper gates as wide as required to ensure that a uniform head of HMA is maintained on the augers. If the augers run continuously with a uniform head of HMA, surges will be avoided. A surge of material will increase the pressure on the screed and create a rough spot on the pavement because the coarse material will be dragged.
Operate the paver continuously. Do not stop and start between truck deliveries.
Operate the paver augers continuously. Adjust the speed so a continuous, uniform and slow flow of material occurs.
Do not run the augers too fast. The center of the mat may not be holding sufficient material when they are running to fast, causing centerline segregation. If a baffle is

installed, the augers in the flights will kick uniform material back to the center.
Alternate paving procedures include material transfer vehicles which can be used to load material into the hopper.
One alternative paving procedure that has been found to reduce segregation involves laying down a windrow in front of the paver rather than dumping the mix directly into the hopper.
The transfer vehicle picks up the HMA from the windrow with paddles, slightly mixing the HMA, then delivers it to a hopper with increased capacity. This process is continuous, which is beneficial since the HMA is slightly remixed and the hopper is never emptied. Segregation caused by improper truck loading, improper transfer to the hopper or improper hopper use could be eliminated.
Another procedure involves a transfer vehicle which has an insulated surge bin with an auger that remixes the HMA before delivering it to the hopper. The truck dumps directly into the transfer vehicle, rather than placing it in a windrow in front of the paver. It is also a continuous process with the same benefits of the windrow, except the HMA is mixed more efficiently, resulting in a more uniform pavement.
These guidelines should minimize segregation in the production and laydown of Hot Mix Asphalt pavements. If the recommendations for proper mix design.....proper operation of the HMA manufacturing facility.....truck loading and paving operations......are followed, segregation should be reduced, hopefully eliminated.

APPENDIX C
Sequence of Steps to Establish Correction Factors

This appendix contains the results of the SAS analysis of the correction factors established for nuclear density and asphalt content. The correction factors were established as follows:

1. Four, one minute readings of density and asphalt content were taken on each sample.
2. These readings were averaged.
3. The average was then compared to known values of density and asphalt content and a correction factor was established for each observation.

The General Linear Model (GLM) procedure was then used to analyze these data. The GLM procedure was used to:

4. Determine the significance of each class (independent factor) to the model. Insignificant factors were dropped from the GLM model. The results contained in this Appendix reflect only the factors that were significant to the model. The discussion of these significant factors is contained in Sections 5.2.4 and 5.2.5.
5. Group the data at 95% confidence as outlined in Tables A.7, A.8, A.18-A.20. The groupings were necessary to identify individual groupings that could require different correction factors (i.e. DOS for Asphalt Content or MIXTYPE for Density).
6. Fit a model of the correction factors and establish a 95% upper and lower confidence interval. These data are contained in Tables A.10 and A.23.

7. Analyze the 95% confidence ranges and establish a standard correction factor for each group. These values are given in Tables 5.7 and 5.8.

Example. The following example outlines Step No.7 for the surface gravel slabs density correction factors. DOS was found to be insignificant to the density model and was dropped model. BSEPAV was also found to be insignificant to the gravel mixtures, so a standard density correction factor could be established for the "group" of surface gravel slabs. Surface gravel slabs were considered a "group" since a common correction factor could be established for all slabs within the 95% confidence range.

Confidence Interval Range	Asphalt Base	Concrete Base
95% Upper Limit	1.00488	1.01321
95% Lower Limit	0.99179	1.00012
Note: Values in this table were taken from Table A.10.		

Table A.1 Density Correction Factor Example - Surface Gravel Slabs

The upper limit of the asphalt base slabs and the lower limit of the concrete base slabs is where the ranges overlapped. A correction factor of 1.002 was selected and applied to each surface gravel slab density reading.

Class	Levels	Values			
DOS	3	COARSE	FINE	UNIFRM	
BSEPAV	2	ASPHALT	CONC		
MIXTYPE	4	BINDGRAV	BINDLIME	SURFGRAV	SURFLIME
Number of observations in data set = 48					

Table A.2 Class Level Information - Nuclear Density

Dependent Variable: CORRND					
Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	7	0.01961458	0.00280208	44.54	0.0001
Error	40	0.00251667	0.00006292		
Corrected Total	47	0.02213125			
		R-Square	C.V.	Root MSE	CORRND Mean
		0.886284	0.802733	0.00793200	0.98812500
Source	DF	Type I SS	Mean Square	F Value	Pr > F
BSEPAV	1	0.00630208	0.00630208	100.17	0.0001
MIXTYPE	3	0.00857292	0.00285764	45.42	0.0001
BSEPAV* MIXTYPE	3	0.00473958	0.00157986	25.11	0.0001
Source	DF	Type III SS	Mean Square	F Value	Pr > F
BSEPAV	1	0.00630208	0.00630208	100.17	0.0001
MIXTYPE	3	0.00857292	0.00285764	45.42	0.0001
BSEPAV* MIXTYPE	3	0.00473958	0.00157986	25.11	0.0001

Table A.3 General Linear Models Procedure - Nuclear Density

BSEPAV	CORRND	Std Err	Pr > |T|
	LSMEAN	LSMEAN	H0:LSMEAN=0
ASPHALT	0.97666667	0.00161911	0.0001
CONC	0.99958333	0.00161911	0.0001

Table A.4 Least Squares Means - BSEPAV

MIXTYPE	CORRND	Std Err	Pr > |T|
	LSMEAN	LSMEAN	H0:LSMEAN=0
BINDGRAV	1.00000000	0.00228977	0.0001
BINDLIME	0.97833333	0.00228977	0.0001
SURFGRAV	1.00250000	0.00228977	0.0001
SURFLIME	0.97166667	0.00228977	0.0001

Table A.5 Least Squares Means - MIXTYPE

BSEPAV	MIXTYPE	CORRND	Std Err	Pr > |T|
		LSMEAN	LSMEAN	H0:LSMEAN=0
ASPHALT	BINDGRAV	1.00000000	0.00323823	0.0001
ASPHALT	BINDLIME	0.95333333	0.00323823	0.0001
ASPHALT	SURFGRAV	0.99833333	0.00323823	0.0001
ASPHALT	SURFLIME	0.95500000	0.00323823	0.0001
CONC	BINDGRAV	1.00000000	0.00323823	0.0001
CONC	BINDLIME	1.00333333	0.00323823	0.0001
CONC	SURFGRAV	1.00666667	0.00323823	0.0001
CONC	SURFLIME	0.99833333	0.00323823	0.0001

Table A.6 Least Squares Means - BSEPAV*MIXTYPE

General Linear Models Procedure

Tukey's Studentized Range (HSD) Test for variable: CORRND

NOTE: This test controls the type I experimentwise error rate, but generally has a higher type II error rate than REGWQ.

Alpha= 0.05 df= 40 MSE= 0.000063
Critical Value of Studentized Range= 2.858
Minimum Significant Difference= 0.0046

Means with the same letter are not significantly different.

Tukey Grouping	Mean	N	BSEPAV
A	0.999583	24	CONC
B	0.976667	24	ASPHALT

Table A.7 Tukey Grouping - BSEPAV

General Linear Models Procedure

Tukey's Studentized Range (HSD) Test for variable: CORRND

NOTE: This test controls the type I experimentwise error rate, but generally has a higher type II error rate than REGWQ.

Alpha= 0.05 df= 40 MSE= 0.000063
Critical Value of Studentized Range= 3.791
Minimum Significant Difference= 0.0087

Means with the same letter are not significantly different.

Tukey Grouping	Mean	N	MIXTYPE
A	1.002500	12	SURFGRAV
A			
A	1.000000	12	BINDGRAV
B	0.978333	12	BINDLIME
B			
B	0.971667	12	SURFLIME

Table A.8 Tukey Grouping - MIXTYPE

Level of	Level of	------------CORRND-----------		
BSEPAV	MIXTYPE	N	Mean	SD
ASPHALT	BINDGRAV	6	1.00000000	0.00632456
ASPHALT	BINDLIME	6	0.95333333	0.01032796
ASPHALT	SURFGRAV	6	0.99833333	0.00408248
ASPHALT	SURFLIME	6	0.95500000	0.00547723
CONC	BINDGRAV	6	1.00000000	0.00632456
CONC	BINDLIME	6	1.00333333	0.01211060
CONC	SURFGRAV	6	1.00666667	0.00816497
CONC	SURFLIME	6	0.98833333	0.00752773

Table A.9 Means - BSEPAV*MIXTYPE

The SAS System

General Linear Models: *Nuclear Density* October 8, 1995

OBS	DOS	BSEPAV	MIXTYPE	CORRND	RESIDND	FITND	LOWND	UPND
1	FINE	ASPHALT	SURFGRAV	1.00	0.001667	0.99833	0.99179	1.00488
2	FINE	ASPHALT	SURFGRAV	0.99	-0.008333	0.99833	0.99179	1.00488
3	UNIFRM	ASPHALT	SURFGRAV	1.00	0.001667	0.99833	0.99179	1.00488
4	UNIFRM	ASPHALT	SURFGRAV	1.00	0.001667	0.99833	0.99179	1.00488
5	COARSE	ASPHALT	SURFGRAV	1.00	0.001667	0.99833	0.99179	1.00488
6	COARSE	ASPHALT	SURFGRAV	1.00	0.001667	0.99833	0.99179	1.00488
7	FINE	CONC	SURFGRAV	1.01	0.003333	1.00667	1.00012	1.01321
8	FINE	CONC	SURFGRAV	1.01	0.003333	1.00667	1.00012	1.01321
9	UNIFRM	CONC	SURFGRAV	1.00	-0.006667	1.00667	1.00012	1.01321
10	UNIFRM	CONC	SURFGRAV	1.00	-0.006667	1.00667	1.00012	1.01321
11	COARSE	CONC	SURFGRAV	1.02	0.013333	1.00667	1.00012	1.01321
12	COARSE	CONC	SURFGRAV	1.00	-0.006667	1.00667	1.00012	1.01321
13	FINE	ASPHALT	SURFLIME	0.96	0.005000	0.95500	0.94846	0.96154
14	FINE	ASPHALT	SURFLIME	0.96	0.005000	0.95500	0.94846	0.96154
15	UNIFRM	ASPHALT	SURFLIME	0.96	0.005000	0.95500	0.94846	0.96154
16	UNIFRM	ASPHALT	SURFLIME	0.95	-0.005000	0.95500	0.94846	0.96154
17	COARSE	ASPHALT	SURFLIME	0.95	-0.005000	0.95500	0.94846	0.96154
18	COARSE	ASPHALT	SURFLIME	0.95	-0.005000	0.95500	0.94846	0.96154
19	FINE	CONC	SURFLIME	0.99	0.001667	0.98833	0.98179	0.99488
20	FINE	CONC	SURFLIME	0.99	0.001667	0.98833	0.98179	0.99488
21	UNIFRM	CONC	SURFLIME	1.00	0.001667	0.98833	0.98179	0.99488
22	UNIFRM	CONC	SURFLIME	0.98	-0.008333	0.98833	0.98179	0.99488
23	COARSE	CONC	SURFLIME	0.99	0.001667	0.98833	0.98179	0.99488
24	COARSE	CONC	SURFLIME	0.98	-0.008333	0.98833	0.98179	0.99488
25	FINE	ASPHALT	BINDGRAV	1.00	0.000000	1.00000	0.99346	1.00654
26	FINE	ASPHALT	BINDGRAV	1.01	0.010000	1.00000	0.99346	1.00654
27	UNIFRM	ASPHALT	BINDGRAV	1.00	0.000000	1.00000	0.99346	1.00654
28	UNIFRM	ASPHALT	BINDGRAV	1.00	0.000000	1.00000	0.99346	1.00654
29	COARSE	ASPHALT	BINDGRAV	0.99	-0.010000	1.00000	0.99346	1.00654
30	COARSE	ASPHALT	BINDGRAV	1.00	0.000000	1.00000	0.99346	1.00654
31	FINE	CONC	BINDGRAV	0.99	-0.010000	1.00000	0.99346	1.00654
32	FINE	CONC	BINDGRAV	1.00	0.000000	1.00000	0.99346	1.00654
33	UNIFRM	CONC	BINDGRAV	1.01	0.010000	1.00000	0.99346	1.00654
34	UNIFRM	CONC	BINDGRAV	1.00	0.000000	1.00000	0.99346	1.00654
35	COARSE	CONC	BINDGRAV	1.00	0.000000	1.00000	0.99346	1.00654
36	COARSE	CONC	BINDGRAV	1.00	0.000000	1.00000	0.99346	1.00654
37	FINE	ASPHALT	BINDLIME	0.95	-0.003333	0.95333	0.94679	0.95988
38	FINE	ASPHALT	BINDLIME	0.94	-0.013333	0.95333	0.94679	0.95988
39	UNIFRM	ASPHALT	BINDLIME	0.95	-0.003333	0.95333	0.94679	0.95988
40	UNIFRM	ASPHALT	BINDLIME	0.97	0.016667	0.95333	0.94679	0.95988
41	COARSE	ASPHALT	BINDLIME	0.95	-0.003333	0.95333	0.94679	0.95988
42	COARSE	ASPHALT	BINDLIME	0.96	0.006667	0.95333	0.94679	0.95988
43	FINE	CONC	BINDLIME	1.01	0.006667	1.00333	0.99679	1.00988
44	FINE	CONC	BINDLIME	0.99	-0.013333	1.00333	0.99679	1.00988
45	UNIFRM	CONC	BINDLIME	1.01	0.006667	1.00333	0.99679	1.00988
46	UNIFRM	CONC	BINDLIME	0.99	-0.013333	1.00333	0.99679	1.00988
47	COARSE	CONC	BINDLIME	1.02	0.016667	1.00333	0.99679	1.00988
48	COARSE	CONC	BINDLIME	1.00	-0.003333	1.00333	0.99679	1.00988

Table A.10 GLM 95% Confidence Intervals for Nuclear Density

Class	Levels	Values			
DOS	3	COARSE	FINE	UNIFRM	
BSEPAV	2	ASPHALT	CONC		
MIXTYPE	4	BINDGRAV	BINDLIME	SURFGRAV	SURFLIME
Number of observations in data set = 48					

Table A.11 Class Level Information - Nuclear Asphalt Content

Dependent Variable: CORRAC					
Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	15	0.90633125	0.06042208	26.53	0.0001
Error	32	0.07286667	0.00227708		
Corrected Total	47	0.97919792			
		R-Square	C.V.	Root MSE	CORRAC Mean
		0.925585	5.293511	0.04771879	0.90145833
Source	DF	Type I SS	Mean Square	F Value	Pr > F
DOS	2	0.11265417	0.05632708	24.74	0.0001
BSEPAV	1	0.12505208	0.12505208	54.92	0.0001
MIXTYPE	3	0.22890625	0.07630208	33.51	0.0001
DOS* MIXTYPE	6	0.04646250	0.00774375	3.40	0.0104
BSEPAV* MIXTYPE	3	0.39325625	0.13108542	57.57	0.0001
Source	DF	Type III SS	Mean Square	F Value	Pr > F
DOS	2	0.11265417	0.05632708	24.74	0.0001
BSEPAV	1	0.12505208	0.12505208	54.92	0.0001
MIXTYPE	3	0.22890625	0.07630208	33.51	0.0001
DOS* MIXTYPE	6	0.04646250	0.00774375	3.40	0.0104
BSEPAV* MIXTYPE	3	0.39325625	0.13108542	57.57	0.0001

Table A.12 General Linear Models Procedure - Nuclear Asphalt Content

DOS	CORRAC	Std Err	Pr > |T|
	LSMEAN	LSMEAN	H0:LSMEAN=0
COARSE	0.84750000	0.01192970	0.0001
FINE	0.96500000	0.01192970	0.0001
UNIFRM	0.89187500	0.01192970	0.0001

Table A.13 Least Squares Means - DOS

BSEPAV	CORRAC	Std Err	Pr > |T|
	LSMEAN	LSMEAN	H0:LSMEAN=0
ASPHALT	0.95250000	0.00974056	0.0001
CONC	0.85041667	0.00974056	0.0001

Table A.14 Least Squares Means - BSEPAV

MIXTYPE	CORRAC	Std Err	Pr > |T|
	LSMEAN	LSMEAN	H0:LSMEAN=0
BINDGRAV	0.94000000	0.01377523	0.0001
BINDLIME	0.79000000	0.01377523	0.0001
SURFGRAV	0.97333333	0.01377523	0.0001
SURFLIME	0.90250000	0.01377523	0.0001

Table A.15 Least Squares Means - MIXTYPE

DOS	MIXTYPE	CORRAC	Std Err	Pr > |T|
		LSMEAN	LSMEAN	H0:LSMEAN=0
COARSE	BINDGRAV	0.82000000	0.02385940	0.0001
COARSE	BINDLIME	0.74250000	0.02385940	0.0001
COARSE	SURFGRAV	0.93750000	0.02385940	0.0001
COARSE	SURFLIME	0.89000000	0.02385940	0.0001
FINE	BINDGRAV	1.03000000	0.02385940	0.0001
FINE	BINDLIME	0.87500000	0.02385940	0.0001
FINE	SURFGRAV	1.02750000	0.02385940	0.0001
FINE	SURFLIME	0.92750000	0.02385940	0.0001
UNIFRM	BINDGRAV	0.97000000	0.02385940	0.0001
UNIFRM	BINDLIME	0.75250000	0.02385940	0.0001
UNIFRM	SURFGRAV	0.95500000	0.02385940	0.0001
UNIFRM	SURFLIME	0.89000000	0.02385940	0.0001

Table A.16 Least Squares Means - DOS*MIXTYPE

BSEPAV	MIXTYPE	CORRAC	Std Err	Pr > |T|
		LSMEAN	LSMEAN	H0:LSMEAN=0
ASPHALT	BINDGRAV	1.11500000	0.01948112	0.0001
ASPHALT	BINDLIME	0.89000000	0.01948112	0.0001
ASPHALT	SURFGRAV	0.94333333	0.01948112	0.0001
ASPHALT	SURFLIME	0.86166667	0.01948112	0.0001
CONC	BINDGRAV	0.76500000	0.01948112	0.0001
CONC	BINDLIME	0.69000000	0.01948112	0.0001
CONC	SURFGRAV	1.00333333	0.01948112	0.0001
CONC	SURFLIME	0.94333333	0.01948112	0.0001

Table A.17 Least Squares Means - BSEPAV*MIXTYPE

General Linear Models Procedure

Tukey's Studentized Range (HSD) Test for variable: CORRAC

NOTE: This test controls the type I experimentwise error rate, but generally has a higher type II error rate than REGWQ.

Alpha= 0.05 df= 40 MSE= 0.002277
Critical Value of Studentized Range= 3.475
Minimum Significant Difference= 0.0415

Means with the same letter are not significantly different.

Tukey Grouping	Mean	N	DOS
A	0.96500	16	FINE
B	0.89188	16	UNIFRM
C	0.84750	16	COARSE

Table A.18 Tukey Grouping - DOS

The SAS System

General Linear Models: *Nuclear Asphalt Content* October 8, 1995

General Linear Models Procedure

Tukey's Studentized Range (HSD) Test for variable: CORRAC

NOTE: This test controls the type I experimentwise error rate, but generally has a higher type II error rate than REGWQ.

Alpha= 0.05 df= 40 MSE= 0.002277
Critical Value of Studentized Range= 2.881
Minimum Significant Difference= 0.0281

Means with the same letter are not significantly different.

Tukey Grouping	Mean	N	BSEPAV
A	0.95250	24	ASPHALT
B	0.85042	24	CONC

Table A.19 Tukey Grouping - BSEPAV

General Linear Models Procedure

Tukey's Studentized Range (HSD) Test for variable: CORRAC

NOTE: This test controls the type I experimentwise error rate, but generally has a higher type II error rate than REGWQ.

Alpha= 0.05 df= 40 MSE= 0.002277
Critical Value of Studentized Range= 3.832
Minimum Significant Difference= 0.0528

Means with the same letter are not significantly different.

Tukey Grouping	Mean	N	MIXTYPE
A	0.97333	12	SURFGRAV
A			
B A	0.94000	12	BINDGRAV
B			
B	0.90250	12	SURFLIME
C	0.79000	12	BINDLIME

Table A.20 Tukey Grouping - MIXTYPE

Level of	Level of	------------CORRAC-----------		
DOS	MIXTYPE	N	Mean	SD
COARSE	BINDGRAV	4	0.82000000	0.23166067
COARSE	BINDLIME	4	0.74250000	0.14660036
COARSE	SURFGRAV	4	0.93750000	0.03403430
COARSE	SURFLIME	4	0.89000000	0.05228129
FINE	BINDGRAV	4	1.03000000	0.18529256
FINE	BINDLIME	4	0.87500000	0.10661457
FINE	SURFGRAV	4	1.02750000	0.07632169
FINE	SURFLIME	4	0.92750000	0.03774917
UNIFRM	BINDGRAV	4	0.97000000	0.21571586
UNIFRM	BINDLIME	4	0.72500000	0.11265730
UNIFRM	SURFGRAV	4	0.95500000	0.03696846
UNIFRM	SURFLIME	4	0.89000000	0.06683313

Table A.21 Means - DOS*MIXTYPE

Level of	Level of	------------CORRAC-----------		
BSEPAV	MIXTYPE	N	Mean	SD
ASPHALT	BINDGRAV	6	1.11500000	0.10858177
ASPHALT	BINDLIME	6	0.89000000	0.06957011
ASPHALT	SURFGRAV	6	0.94333333	0.03881580
ASPHALT	SURFLIME	6	0.86166667	0.03868678
CONC	BINDGRAV	6	0.76500000	0.11895377
CONC	BINDLIME	6	0.69000000	0.08485281
CONC	SURFGRAV	6	1.00333333	0.07061633
CONC	SURFLIME	6	0.94333333	0.02065591

Table A.22 Means - BSEPAV*MIXTYPE

The SAS System

General Linear Models: *Nuclear Asphalt Content* October 8, 1995

OBS	DOS	BSEPAV	MIXTYPE	CORRAC	RESIDAC	FITAC	LOWAC	UPAC
1	FINE	ASPHALT	SURFGRAV	0.96	-0.037500	0.99750	0.94138	1.05362
2	FINE	ASPHALT	SURFGRAV	0.97	-0.027500	0.99750	0.94138	1.05362
3	UNIFRM	ASPHALT	SURFGRAV	0.91	-0.015000	0.92500	0.86888	0.98112
4	UNIFRM	ASPHALT	SURFGRAV	1.00	0.075000	0.92500	0.86888	0.98112
5	COARSE	ASPHALT	SURFGRAV	0.91	0.002500	0.90750	0.85138	0.96362
6	COARSE	ASPHALT	SURFGRAV	0.91	0.002500	0.90750	0.85138	0.96362
7	FINE	CONC	SURFGRAV	1.06	0.002500	1.05750	1.00138	1.11362
8	FINE	CONC	SURFGRAV	1.12	0.062500	1.05750	1.00138	1.11362
9	UNIFRM	CONC	SURFGRAV	0.96	-0.025000	0.98500	0.92888	1.04112
10	UNIFRM	CONC	SURFGRAV	0.95	-0.035000	0.98500	0.92888	1.04112
11	COARSE	CONC	SURFGRAV	0.98	0.012500	0.96750	0.91138	1.02362
12	COARSE	CONC	SURFGRAV	0.95	-0.017500	0.96750	0.91138	1.02362
13	FINE	ASPHALT	SURFLIME	0.92	0.033333	0.88667	0.83055	0.94279
14	FINE	ASPHALT	SURFLIME	0.89	0.003333	0.88667	0.83055	0.94279
15	UNIFRM	ASPHALT	SURFLIME	0.86	0.010833	0.84917	0.79305	0.90529
16	UNIFRM	ASPHALT	SURFLIME	0.81	-0.039167	0.84917	0.79305	0.90529
17	COARSE	ASPHALT	SURFLIME	0.84	-0.009167	0.84917	0.79305	0.90529
18	COARSE	ASPHALT	SURFLIME	0.85	0.000833	0.84917	0.79305	0.90529
19	FINE	CONC	SURFLIME	0.92	-0.048333	0.96833	0.91221	1.02445
20	FINE	CONC	SURFLIME	0.98	0.011667	0.96833	0.91221	1.02445
21	UNIFRM	CONC	SURFLIME	0.95	0.019167	0.93083	0.87471	0.98695
22	UNIFRM	CONC	SURFLIME	0.94	0.009167	0.93083	0.87471	0.98695
23	COARSE	CONC	SURFLIME	0.93	-0.000833	0.93083	0.87471	0.98695
24	COARSE	CONC	SURFLIME	0.94	0.009167	0.93083	0.87471	0.98695
25	FINE	ASPHALT	BINDGRAV	1.11	-0.095000	1.20500	1.14888	1.26112
26	FINE	ASPHALT	BINDGRAV	1.25	0.045000	1.20500	1.14888	1.26112
27	UNIFRM	ASPHALT	BINDGRAV	1.08	-0.065000	1.14500	1.08888	1.20112
28	UNIFRM	ASPHALT	BINDGRAV	1.22	0.075000	1.14500	1.08888	1.20112
29	COARSE	ASPHALT	BINDGRAV	0.95	-0.045000	0.995	0.93888	1.05112
30	COARSE	ASPHALT	BINDGRAV	1.08	0.085000	0.995	0.93888	1.05112
31	FINE	CONC	BINDGRAV	0.84	-0.015000	0.85500	0.79888	0.91112
32	FINE	CONC	BINDGRAV	0.92	0.065000	0.85500	0.79888	0.91112
33	UNIFRM	CONC	BINDGRAV	0.78	-0.015000	0.79500	0.73888	0.85112
34	UNIFRM	CONC	BINDGRAV	0.80	0.005000	0.79500	0.73888	0.85112
35	COARSE	CONC	BINDGRAV	0.61	-0.035000	0.64500	0.58888	0.70112
36	COARSE	CONC	BINDGRAV	0.64	-0.005000	0.64500	0.58888	0.70112
37	FINE	ASPHALT	BINDLIME	0.95	-0.025000	0.97500	0.91888	1.03112
38	FINE	ASPHALT	BINDLIME	0.98	0.005000	0.97500	0.91888	1.03112
39	UNIFRM	ASPHALT	BINDLIME	0.79	-0.062500	0.85250	0.79638	0.90862
40	UNIFRM	ASPHALT	BINDLIME	0.89	0.016667	0.85250	0.79638	0.90862
41	COARSE	ASPHALT	BINDLIME	0.84	-0.002500	0.84250	0.78638	0.89862
42	COARSE	ASPHALT	BINDLIME	0.89	0.0475	0.84250	0.78638	0.89862
43	FINE	CONC	BINDLIME	0.76	-0.015000	0.7750	0.71888	0.83112
44	FINE	CONC	BINDLIME	0.81	0.0350	0.7750	0.71888	0.83112
45	UNIFRM	CONC	BINDLIME	0.63	-0.0225	0.6525	0.59638	0.70862
46	UNIFRM	CONC	BINDLIME	0.70	0.0475	0.6525	0.59638	0.70862
47	COARSE	CONC	BINDLIME	0.58	-0.0625	0.6425	0.58638	0.69862
48	COARSE	CONC	BINDLIME	0.66	0.0175	0.6425	0.58638	0.69862

Table A.23 GLM 95% Confidence Intervals for Nuclear Asphalt Content

APPENDIX D
Discriminant Analysis Output of Laboratory Nuclear Gauge Testing

Discriminant Analysis

24 Observations	23 DF Total
2 Variables	21 DF Within Classes
3 Classes	2 DF Between Classes

	Prior			
DOS	Frequency	Weight	Proportion	Probability
COARSE	8	8.0000	0.333333	0.333333
FINE	8	8.0000	0.333333	0.333333
UNIFRM	8	8.0000	0.333333	0.333333

Table B.1 Class Level Infromation - Surface Mixtures

Pooled Within-Class Covariance Matrix, DF = 21		
Variable	CORRND	CORRAC
CORRND	13.98593452	-0.36292857
CORRAC	-0.36292857	0.10636905

Table B.2 Covariance Matrix - Surface Mixtures

Pooled Covariance Matrix Information	
Covariance Matrix Rank	Natural Log of the Determinant of the Covariance Matrix
2	0.30450481

Table B.3 Covariance Matrix Information- Surface Mixtures

Pairwise Generalized Squared Distances Between Groups			
$D^2_{(i\|j)} = (\bar{X}_i - \bar{X}_j)\ COV^{-1}(\bar{X}_i - \bar{X}_j)$			
From DOS	COARSE	FINE	UNIFRM
COARSE	0	33.51184	12.43648
FINE	33.51184	0	6.41271
UNIFRM	12.43648	6.41271	0

Table B.4 Generalized Squared Distance to DOS - Surface Mixtures

Linear Discriminant Function			
Constant = $-.5\ \bar{X}_j'\ COV^{-1}\bar{X}_j$		Coefficient Vector = $COV^{-1}\bar{X}_j$	
DOS	COARSE	FINE	UNIFRM
CONSTANT	-1044	-1238	-1185
CORRND	12.10054	12.73494	12.70180
CORRAC	87.00023	105.49942	97.63035

Table B.5 Linear Discriminant Function - Surface Mixtures

Classification Summary for Calibration Data: WORK.BNDRMXS				
Generalized Squared Distance Function:	Posterior Probability of Membership in each DOS:			
$D^2(X_j) = (X-\bar{X}_j)'COV^{-1}(X-\bar{X}_j)$	$Pr(j\|X) = exp(-.5\ D^2_j(X)) / SUM_k exp(-.5\ D^2_k(X))$			
Number of Observations and Percent Classified into DOS:				
From DOS	COARSE	FINE	UNIFRM	Total
COARSE	8	0	0	8
	100.00	0.00	0.00	100.00
FINE	0	6	2	8
	0.00	75.00	25.00	100.00
UNIFRM	0	1	7	8
	0	12.50	87.5	100.00
Total	8	7	9	24
Percent	33.33	29.17	37.50	100.00
Priors	0.3333	0.3333	0.3333	
Error Count Estimates for DOS:				
	COARSE	FINE	UNIFRM	Total
Rate	0.0000	0.25	0.125	0.125
Priors	0.3333	0.3333	0.3333	

Table B.6 Resubstitution Summary using Linear Discriminant Function - Surface Mixtures

Classification Results for Calibration Data: WORK.BNDRMXS						
Generalized Squared Distance Function:				Posterior Probability of Membership in each DOS:		
$D^2(X_j) = (X-\bar{X}_j)'COV^{-1}(X-\bar{X}_j)$				$Pr(j\|X) = \exp(-.5\ D^2_j(X)) / SUM_k \exp(-.5\ D^2_k(X))$		
		Classified				
Observation		From	Into	Posterior Probability of Membership in DOS:		
	BASE	DOS	DOS	COARSE	FINE	UNIFRM
	PVMT					
Surface Gravel Mix						
1	AC	FINE	FINE	0.0000	0.9991	0.0009
2	AC	FINE	FINE	0.0000	0.9980	0.0020
3	AC	UNIFRM	FINE *	0.0001	0.6763	0.3236
4	AC	UNIFRM	UNIFRM	0.0571	0.0180	0.9250
5	AC	COARSE	COARSE	0.9980	0.0000	0.0020
6	AC	COARSE	COARSE	0.9986	0.0000	0.0014
7	CONC	FINE	FINE	0.0000	0.9993	0.0007
8	CONC	FINE	FINE	0.0000	0.9917	0.0083
9	CONC	UNIFRM	FINE	0.0001	0.1057	0.8942
10	CONC	UNIFRM	UNIFRM	0.0000	0.2157	0.7843
11	CONC	COARSE	COARSE	0.9992	0.0000	0.0008
12	CONC	COARSE	COARSE	0.9610	0.0000	0.0390
Surface Limestone Mix						
13	AC	FINE	UNIFRM *	0.0019	0.1712	0.8269
14	AC	FINE	UNIFRM *	0.0004	0.3154	0.6842
15	AC	UNIFRM	UNIFRM	0.0831	0.0040	0.9129
16	AC	UNIFRM	UNIFRM	0.0031	0.0450	0.9519
17	AC	COARSE	COARSE	0.9996	0.0000	0.0004
18	AC	COARSE	COARSE	0.9999	0.0000	0.0001
19	CONC	FINE	FINE	0.0000	0.9300	0.0700
20	CONC	FINE	FINE	0.0000	0.5439	0.4561
21	CONC	UNIFRM	UNIFRM	0.0220	0.0047	0.9734
22	CONC	UNIFRM	UNIFRM	0.0018	0.0055	0.9927
23	CONC	COARSE	COARSE	0.9941	0.0000	0.0059
24	CONC	COARSE	COARSE	0.9922	0.0000	0.0078

* Misclassified Observation

Table B.7 Classification Results - Surface Mixtures

Discriminant Analysis

24 Observations	23 DF Total
2 Variables	21 DF Within Classes
3 Classes	2 DF Between Classes

Class Level Information

			Prior	
DOS	Frequency	Weight	Proportion	Probability
COARSE	8	8.0000	0.333333	0.333333
FINE	8	8.0000	0.333333	0.333333
UNIFRM	8	8.0000	0.333333	0.333333

Table B.8 Class Level Infromation - Binder Mixtures

Pooled Within-Class Covariance Matrix. DF = 21		
Variable	CORRND	CORRAC
CORRND	24.46442083	-0.88010119
CORRAC	-0.88010119	0.19851190

Table B.9 Covariance Matrix - Binder Mixtures

Pooled Covariance Matrix Information	
Covariance Matrix Rank	Natural Log of the Determinant of the Covariance Matrix
2	1.40656273

Table B.10 Covariance Matrix Information- Binder Mixtures

Pairwise Generalized Squared Distances Between Groups			
$D^2_{(i\|j)} = (\bar{X}_i - \bar{X}_j)\ COV^{-1}(\bar{X}_i - \bar{X}_j)$			
From DOS	COARSE	FINE	UNIFRM
COARSE	0	42.54470	13.92287
FINE	42.54470	0	7.94034
UNIFRM	13.92287	7.94034	0

Table B.11 Generalized Squared Distance to DOS - Binder Mixtures

Linear Discriminant Function			
Constant = $-.5\ \bar{X}_j'\ COV^{-1}\bar{X}_j$		Coefficient Vector = $COV^{-1}\bar{X}_j$	
DOS	COARSE	FINE	UNIFRM
CONSTANT	-581.10598	-767.21384	-688.75017
CORRND	7.32299	8.14311	7.84356
CORRAC	49.78275	65.44573	58.57648

Table B.12 Linear Discriminant Function - Binder Mixtures

Classification Summary for Calibration Data: WORK.BNDRMXS				
Generalized Squared Distance Function:	Posterior Probability of Membership in each DOS:			
$D^2(X_j) = (X-\bar{X}_j)' COV^{-1}(X-\bar{X}_j)$	$Pr(j\|X) = exp(-.5\ D^2_j(X)) / SUM_k exp(-.5\ D^2_k(X))$			
Number of Observations and Percent Classified into DOS:				
From DOS	COARSE	FINE	UNIFRM	Total
COARSE	8	0	0	8
	100.00	0.00	0.00	100.00
FINE	0	8	0	8
	0.00	100.00	0.00	100.00
UNIFRM	0	1	7	8
	0	12.50	87.5	100.00
Total	8	9	7	24
Percent	33.33	37.5	29.17	100.00
Priors	0.3333	0.3333	0.3333	
Error Count Estimates for DOS:				
	COARSE	FINE	UNIFRM	Total
Rate	0.0000	0.0000	0.125	0.0417
Priors	0.3333	0.3333	0.3333	

Table B.13 Resubstitution Summary using Linear Discriminant Function - Binder Mixtures

Classification Results for Calibration Data: WORK.BNDRMXS						
Generalized Squared Distance Function:				Posterior Probability of Membership in each DOS:		
$D^2(X_j) = (X-\bar{X}_j)'COV^{-1}(X-\bar{X}_j)$				$Pr(j\|X) = exp(-.5\ D^2_j(X)) / SUM_k exp(-.5\ D^2_k(X))$		
		Classified				
Observation		From	Into	Posterior Probability of Membership in DOS:		
	BASE PVMT	DOS	DOS	COARSE	FINE	UNIFRM
Binder Gravel Mix						
1	AC	FINE	FINE	0.0000	0.9996	0.0004
2	AC	FINE	FINE	0.0000	0.9210	0.0790
3	AC	UNIFRM	UNIFRM	0.0000	0.3446	0.6554
4	AC	UNIFRM	UNIFRM	0.0097	0.0055	0.9848
5	AC	COARSE	COARSE	0.9982	0.0000	0.0018
6	AC	COARSE	COARSE	1.0000	0.0000	0.0000
7	CONC	FINE	FINE	0.0000	0.9994	0.0006
8	CONC	FINE	FINE	0.0000	0.9807	0.0193
9	CONC	UNIFRM	FINE *	0.0000	0.5170	0.4830
10	CONC	UNIFRM	UNIFRM	0.0000	0.4382	0.5618
11	CONC	COARSE	COARSE	0.8761	0.0000	0.1239
12	CONC	COARSE	COARSE	0.9536	0.0000	0.0464
Binder Limestone Mix						
13	AC	FINE	FINE	0.0000	0.9433	0.0567
14	AC	FINE	FINE	0.0000	0.8443	0.1557
15	AC	UNIFRM	UNIFRM	0.0039	0.0065	0.9895
16	AC	UNIFRM	UNIFRM	0.4289	0.0001	0.5710
17	AC	COARSE	COARSE	1.0000	0.0000	0.0000
18	AC	COARSE	COARSE	1.0000	0.0000	0.0000
19	CONC	FINE	FINE	0.0000	0.9726	0.0274
20	CONC	FINE	FINE	0.0000	0.8940	0.1060
21	CONC	UNIFRM	UNIFRM	0.0018	0.0071	0.9911
22	CONC	UNIFRM	UNIFRM	0.0142	0.0010	0.9847
23	CONC	COARSE	COARSE	0.9739	0.0000	0.0261
24	CONC	COARSE	COARSE	0.9994	0.0000	0.0006

* Misclassified Observation

Table B.14 Classification Results - Binder Mixtures

APPENDIX E
Discriminant Analysis Output of Field Nuclear Gauge Testing

Discriminant Analysis

12 Observations	11 DF Total
2 Variables	10 DF Within Classes
2 Classes	1 DF Between Classes

Class Level Information

SEG	Frequency	Weight	Proportion	Prior Probability
coar	4	4.0000	0.333333	0.333333
none	8	8.0000	0.666667	0.666667

Discriminant Analysis

Total-Sample Standardized Class Means

Variable	coar	none
PASP	-0.115605269	0.057802634
PDENS	-1.091816438	0.545908219

Pooled Within-Class Standardized Class Means

Variable	coar	none
PASP	-0.110629268	0.055314634
PDENS	-1.760165377	0.880082688

Discriminant Analysis   Pooled Covariance Matrix Information

Covariance Matrix Rank	Natural Log of the Determinant of the Covariance Matrix
2	7.74362331

Discriminant Analysis Pairwise Generalized Squared Distances Between Groups

$$D^2(i|j) = (\bar{X}_i - \bar{X}_j)' \, COV^{-1} \, (\bar{X}_i - \bar{X}_j) - 2 \ln PRIOR_j$$

Generalized Squared Distance to SEG

From SEG	coar	none
coar	2.19722	22.93745
none	24.32374	0.81093

$$\text{Constant} = -.5 \, \bar{X}_j' \, COV^{-1} \, \bar{X}_j - \ln PRIOR_j \qquad \text{Coefficient Vector} = COV^{-1} \, \bar{X}_j$$

SEG

	coar	none
CONSTANT	-767.84897	-961.29586
PASP	3.30179	3.67287
PDENS	14.34015	16.08011

Discriminant Analysis   Classification Summary for Calibration Data: WORK.SEG

Resubstitution Summary using Linear Discriminant Function

Generalized Squared Distance Function:

$$D_j^2(X) = (X-\bar{X}_j)' \, COV^{-1} \, (X-\bar{X}_j) - 2 \ln PRIOR_j$$

Posterior Probability of Membership in each SEG:

$$Pr(j|X) = \exp(-.5 \, D_j^2(X)) \, / \, SUM_k \exp(-.5 \, D_k^2(X))$$

Number of Observations and Percent Classified into SEG:

From SEG	coar	none	Total
coar	4 100.00	0 0.00	4 100.00
none	0 0.00	8 100.00	8 100.00
Total Percent	4 33.33	8 66.67	12 100.00
Priors	0.3333	0.6667	

Error Count Estimates for SEG:

	coar	none	Total
Rate	0.0000	0.0000	0.0000
Priors	0.3333	0.6667	

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